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TRW, Inc, Redondo Beach, CA

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The report compares the costs and environmental impacts associated with the disposal of liquid organochlorine wastes by land-based incineration, at-sea incineration, and chlorolysis at a Houston, Texas, location. All three methods are viable options for the disposal of these wastes. At typical unit disposal costs of \$80 to \$91 per metric ton, at-sea incineration is the least costly option. Comparable costs are \$181 to \$212 per metric ton at a centralized land-based incinerator, and \$134 to \$158 per metric ton by the Hoechst-Uhde chlorolysis process if suitable feedstocks are available. Environmentally, maximum ground level concentrations of inorganic chlorine and organochlorine species and particulates emitted from land-based incinerators and chlorolysis are all several orders of magnitude lower than their respective Threshold Limit Values (TLVs) or are within air quality standards. The only wastewater problem identified for both disposal processes is discharges with high total dissolved solids. For at-sea incineration, the maximum sea level concentration of hydrogen chloride is 4.4 mg/cu m and below its TLV of 7 mg/cu m. The maximum sea level concentration of unburned wastes is several orders of magnitude lower than the TLV of most organochlorine compounds. Water quality is not measurably impacted by at-sea incineration.

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1. INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Liquid organochlorine residues are generated by a variety of industrial processes for the production of materials such as vinyl chloride monomer, chlorinated solvents, and pesticides. Estimated chlorinated organics production and the resulting organochlorine residues generated in the United States are presented in Table 1.

TABLE 1. PRODUCTION OF CHLORINE, CHLORINATED ORGANICS AND ORGANOCHLORINE RESIDUES IN THE UNITED STATES

Item	Quantity Produced, Thousands of Metric Tons				
	1965	1967	1970	1975	1978
Chlorine	5,912	6,967	8,854	10,487	12,700
Chlorinated Organics	6,622	7,575	8,709	11,793	14,290
Organochlorine Residues	247	272	298	389	472
Percent Residues	3.73%	3.60%	3.41%	3.30%	3.30%
Average % Chlorine in Residues	58.1 %	58.7 %	60.1 %	60.6 %	60.6 %

Source: The 1965, 1967, 1970 and 1975 figures were obtained from Reference 1. The 1978 figures were extrapolated from the 1975 figures by using the projected 1978 chlorine production and assuming that the chlorinated organics/chlorine production ratio will be the same as that in 1975.

Liquid organochlorine residues requiring disposal are generally nonaqueous, contain 50 to 70 percent by weight of chlorine, and have heating values in the 9,300 to 14,000 kJ/kg (4,000 to 6,000 Btu/lb) range. These wastes can also be mixed with each other without chemical reactions or heat effects.

Various methods of disposal for these organochlorine wastes include land burial, deep well injection, chemical destruction, land-based incineration followed by neutralization, land-based incineration with hydrogen chloride recovery, at-sea incineration, and recovery processes such as chlorolysis. Three of the common methods for the disposal of liquid organochlorine wastes are considered in the present study: conventional land-based incineration followed by scrubbing and neutralization of the hydrogen chloride formed, at-sea incineration utilizing shipboard incinerators, and chlorolysis, a process for converting organochlorine wastes to carbon tetrachloride as a saleable product. Objectives of this study are to compare the costs and the environmental impacts associated with these three disposal methods.

In cost analysis, the overall approach utilized consists of the following elements: (1) determine the capital investment cost and annual operating costs for a representative disposal facility; (2) calculate the unit costs, in terms of $ per metric ton, for the disposal of a number of representative organochlorine wastes by using the discounted cash flow technique; (3) identify the cost sensitive parameters and assess the effects of these parameters on the unit disposal cost; and (4) compare the calculated unit disposal costs with the actual costs charged by waste disposal operators, wherever possible. Steps involved in environmental assessment include: (1) identify the air emissions and liquid and solid discharges from the disposal process; (2) generally characterize the transport and fate of the pollutant materials within air, water, and land environments; and (3) identify and predict the general environmental impacts that may result from the effects of these pollutants on air and water quality. Results of cost analysis and environment assessment for the three disposal processes are compared, integrated, and summarized in this report.

The primary data base for the analysis performed in this study is comprised of two EPA sponsored studies (References 2 and 3), plus additional information provided by operators of land-based and shipboard incinerators. Results from the first EPA sponsored study, "Environmental Assessment - At-Sea and Land-Based Incineration of Organochlorine Wastes", form the basis of discussion of environmental impacts of land-based and at-sea incineration in this report. The second EPA sponsored study, "Chlorolysis Applied to the Conversion of Chlorocarbon Residues Possibly Containing Oxygenated Analogs", provides material balance and cost information needed to characterize the emissions from chlorolysis and to calculate the unit disposal costs for chlorolysis.

In the comparative cost analysis and environmental assessment, the facility operated by Rollins Environmental Services, Inc., located at Houston, Texas was selected as the model representative of land-based incineration. This is a centralized incineration facility extensively used for the contract disposal of organochlorine wastes, and has the capacity for disposal of 23,420 metric tons of liquid organochlorine wastes per year. Cost analysis and environmental assessment for at-sea incineration were based on the M/T Vulcanus, which has the capacity for incinerating 69,000 metric tons per year of liquid organochlorine wastes, at an average incineration rate of 23 metric tons per hour and assuming 3000 hours of incinerator operation per year. For chlorolysis, the Hoechst-Uhde plant design for processing 25,000 metric tons per year of liquid organochlorine wastes was the basis for analysis. The comparative analysis performed was for these plant capacities representative of commercial scale operations, and no attempt was made to address disposal costs and environmental impacts on a common capacity basis.

It has been estimated that approximately 80 percent of the U.S. organochlorine wastes are generated along the Gulf Coast. To eliminate the cost of waste transportation from consideration, a Houston, Texas location was selected for analyzing all three waste disposal options.

Theoretically, most pumpable liquid organochlorine wastes could be disposed of by land-based or shipboard incineration. The major requirements are that the waste should not be corrosive, and/or contain more than 1 percent solid particulates and trace element levels that could have adverse effects on the environment. For chlorolysis, acceptable feedstocks should be free of particulates and should not contain nitrogen or phosphorus. Additional restrictions for chlorolysis feedstocks are that the sulfur content should not exceed 25 ppm because of material corrosion problems, and the aromatic hydrocarbon content should not exceed 5 weight percent because of material temperature limitations. Chlorolysis is, therefore, more suited for the disposal of aliphatic chlorinated hydrocarbons, and for wastes as produced in the manufacture of vinyl chloride monomer (VCM) and chlorinated solvents.

Although a wide variety of liquid organochlorine wastes could be disposed of by either of the three alternative methods, five typical wastes were selected for the comparative economic analysis. The five wastes included a perchloroethylene waste, a hexachlorocyclopentadiene waste, a mixed VCM and chlorinated solvent waste, a VCM waste, and a waste produced during the manufacture of allyl chloride, epichlorohydrin, dichloroethane, and vinyl chloride (hereafter referred to as the combined manufacturing waste, or CMW). The mixed VCM and chlorinated solvent waste and the VCM waste were selected because both wastes are suitable feedstocks for chlorolysis and have been analyzed in the Hoechst-Uhde report (Reference 3). The CMW waste was selected because the waste composition and physical properties are representative of the average of organochlorine wastes, and because the waste has been successfully burned on board the M/T Vulcanus. The perchloroethylene and hexachlorocyclopentadiene wastes were selected to examine the effects of chlorine content and heating value on the cost of disposal. Strictly speaking, the CMW waste, the perchloroethylene waste, and the hexachlorocyclopentadiene waste are not suitable feedstocks for chlorolysis. The sulfur contents for the CMW waste and the hexachlorocyclopentadiene waste are 90 ppm and 200 ppm, respectively, both exceeding the 25 ppm sulfur limit. The perchloroethylene waste contains 9.2 percent by weight of chlorinated benzene, exceeding the 5 percent by weight limit for aromatics. However, all three wastes can be blended with VCM wastes to meet the chlorolysis feedstock acceptability criteria.

In environmental impact analysis, the CMW waste was considered for both land-based and shipboard incineration. Again, this was because the CMW waste is representative of the average of organochlorine wastes, and measured emissions data are available from tests conducted on board the M/T Vulcanus. The mixed VCM and chlorinated solvent waste was considered in the environmental impact analysis for chlorolysis, because it is the most probable feedstock and the base case analyzed by Hoechst-Uhde. Comparative environment assessment was not performed for five typical organochlorine wastes, as was in the case of cost analysis, due to the paucity of measured emissions data.

This report consists of five sections, the first of which is the introduction and summary of all significant findings. Section 2 provides a general description and results of cost analysis and environmental assessment for land-based incineration. Sections 3 and 4 are organized in the same fashion as Section 2, and discuss at-sea incineration and chlorolysis, respectively. In Section 5, costs and environmental impacts associated with the disposal of organochlorine wastes by the three alternative methods are compared. Appendix A presents the cost model utilized in the calculation of unit disposal costs. The model used for air quality simulation is described in Appendix B.

1.2 SUMMARY

The present study has demonstrated that land-based incineration, at-sea incineration, and chlorolysis are all viable options for the disposal of liquid organochlorine wastes. The attractiveness of each disposal method depends on the physical and chemical characteristics of the waste requiring disposal, the market demand for saleable products generated, and the waste volume of concern. The major findings of the analysis performed are summarized in Table 2 and discussed as follows.

TABLE 2. COMPARISON OF DISPOSAL METHODS FOR ORGANOCHLORINE WASTES

Disposal Method	Process Applicability	Unit Disposal Cost*, \$/Metric Ton	Environmental Impacts	Potential Malfunctions
Land-based Incineration	Suited for the disposal of other types of liquid wastes as well as sludges, solids, semi-solids and contaminated containers.	181-212	Maximum ground level HCl concentration is three orders of magnitude lower than Threshold Limit Value (TLV). Unburned wastes were not detected. Scrubber wastewater contains high total dissolved solids (TDS).	Incinerator flameout, spills and leaks due to seal deterioration, mechanical failure, or manual errors, tank overfill.
At-sea Incineration	Applicable to the disposal of other types of liquid wastes; however, liquid wastes requiring disposal should not contain more than 1 percent solid particulates.	80-91	Maximum sea level HCl concentration is below TLV. Maximum sea level concentration of unburned waste is 2.8 $\mu g/m^3$. Water quality is not measurably impacted.	Incinerator flameout, spills during loading, spills and leaks due to seal and pump failures.
Chlorolysis	Suited for the disposal of liquid aliphatic chlorinated hydrocarbons only. Acceptable feedstocks should be free of particulates, and contain less than 25 ppm sulfur and less than 5 weight percent aromatic hydrocarbons.	136-196	Maximum ground level concentrations of HCl, Cl_2, $COCl_2$, CCl_4 and SO_2 are several orders of magnitude lower than their respective TLV's. Scrubber wastewater contains high TDS, but the water quality impacts are less than would be expected from land-based incineration. Credit should be given for resource recovery.	Tank overfill, incineration flameout, spills and leaks due to seal and pump failures.

* Unit disposal costs for land-based incineration and chlorolysis were calculated at 15% discounted cash flow rate of return. Unit disposal costs for at-sea incineration were based on prices charged by Ocean Combustion Services, B.V.

- The capital investment cost of a land-based incineration facility located in the Houston, Texas area, with a heat release rate of 100 GJ per hour (95 million Btu per hour) and average liquid feed rate of 2.27 cubic meters per hour (600 gallons per hour), is $4,600,000.

- At 15% discounted cash flow rate of return (DCFRR), the unit cost of disposal of liquid organochlorine wastes at a centralized land-based incineration facility ranges from $181 to $212 per metric ton, depending on the chlorine and heat content of the waste. The unit disposal costs calculated at 15% DCFRR are in good agreement with actual costs charged by contract waste disposal companies.

- Reliable capital investment and operating costs for at-sea incineration are not available at the present time. However, preliminary estimates by Global Marine Development Inc. have indicated that the capital investment cost of modifying a World War II T2 tanker to an at-sea incineration vessel would be $10,400,000. Such a vessel would have a load capacity of 12,000 metric tons and an incineration rate of 95 metric tons per hour.

- Based on prices charged by Ocean Combustion Services, B.V., the unit cost of disposal of liquid organochlorine wastes by at-sea incineration ranges from $80 to $91 per metric ton, depending on the heat content of the waste. Unit disposal costs by at-sea incineration were not calculated using the discounted cash flow technique because of the absence of reliable financial data.

- The capital investment cost for a chlorolysis plant processing 25,000 metric tons of organochlorine waste per year is $27,210,000, based on the Hoechst-Uhde design and a Gulf Coast location such as Houston, Texas.

- At a carbon tetrachloride selling price of $300 per metric ton and assuming 15% DCFRR, the unit cost for the disposal of organochlorine wastes by chlorolysis ranges from $134 to $196 per metric ton, depending on the chemical composition of the waste.

- Disposal by chlorolysis is favored for organochlorine wastes with higher carbon content and lower hydrogen and oxygen content, such as the perchloroethylene wastes, the mixed VCM and solvent waste, and the VCM waste. At a carbon tetrachloride selling price of $300 per metric ton and 15% DCFRR, chlorolysis has a cost advantage of $45 to $76 per metric ton over land-based incineration for the disposal of these organochlorine wastes.

- In terms of unit disposal costs, land-based incineration is considerably more expensive than at-sea incineration, mainly due to the cost of hydrated lime needed for the neutralization of hydrochloric acid, and the higher unit costs for capital related charges and operating labor.

- The unit disposal cost of organochlorine wastes by chlorolysis is very sensitive to the carbon tetrachloride selling price. At a carbon tetrachloride selling price of around $285 per metric ton and 15% DCFRR, chlorolysis becomes less attractive than land-based incineration for the disposal of the mixed vinyl chloride monomer and chlorinated solvent waste and the vinyl chloride monomer waste. At a carbon tetrachloride selling price of around $315 per metric ton and 15% DCFRR, chlorolysis becomes increasingly cost competitive with at-sea incineration for the disposal of these two organochlorine wastes.

- Land-based incineration cannot be cost competitive with at-sea incineration, because the net operating cost for land-based incineration, without taking into account any return on investment, is higher than the unit disposal costs charged for at-sea incineration.

- For chlorolysis, the charges for the disposal of organochlorine wastes only represent a fraction of the total annual revenue. By lowering the DCFRR to the 10.8 to 13.4% range, chlorolysis can be made to be cost competitive with at-sea incineration for the disposal of organochlorine wastes, at a carbon tetrachloride selling price of $300 per metric ton.

- The maximum ground level concentrations of hydrogen chloride and unburned wastes emitted from land-based incineration are 540 and 180 ng/m^3, respectively. These levels are several orders of magnitude lower than their respective Threshold Limit Values (TLV's). Water quality impacts of the scrubber water will be reflected in the need for additional downstream treatment and in possible adverse effects of high total dissolved solids (TDS).

- The maximum sea level concentration of hydrogen chloride from at-aea incineration is below its Threshold Limit Value (TLV) of 7 mg/m^3. The predicted maximum sea level concentration of unburned waste, based on the lowest observed destruction efficiency of 99.96 percent, is 2.75 μg/m^3. Water quality is not measurably impacted.

- The predicted ground level concentrations of hydrogen chloride, chlorine, carbonyl chloride, carbon tetrachloride, and sulfur dioxide at distances downwind from a chlorolysis plant are several orders of magnitude lower than their respective TLV's. Wastewater from the chlorolysis process has high TDS. However, water quality impacts resulting from chlorolysis, in terms of TDS, are much less than would be expected from land-based incineration.

- In all three cases compared, trace element emissions are dependent upon their concentrations in the feedstock.

- Chlorolysis has an apparent ecological advantage over the other two disposal options in that chemical wastes are recycled to yield saleable products. Thus, an environmental credit should be given equal to the emissions that would have resulted from the manufacture of equivalent quantities of carbon tetrachloride.

- The largest spill possibility at a land-based incineration facility exists in the storage tank and transfer area. All of this area should be paved, diked, and drained to a catch basin with pumped return to storage tanks. The other major failure cause could come from incineration malfunctions, such as burner flameout. Well-designed combustion controls, however, should provide a large amount of protection against these potential problems.

- The greatest possibility of spills related to at-sea incineration occurs during loading. To prevent flameout, a positive and rapid waste feed shutoff system must be available.

- The Hoechst-Uhde chlorolysis design is considerably more complex, from an equipment standpoint, than land-based or at-sea incineration. Increased complexity generally leads to increased reliability problems, but the use of redundant equipment and maintenance surveillance associated with general chemical plant practice will minimize equipment failure problems.

- Chlorolysis should be considered as a desirable disposal method for liquid organochlorine wastes if the selling price for carbon tetrachloride remains stable, mainly because it conserves resources and causes minimum environmental damage. However, only approximately 10 percent of the organochlorine wastes generated in the U.S. are available and considered as suitable feedstocks for chlorolysis.

- At-sea incineration is most cost-effective for the disposal of large quantities of liquid organochlorine wastes. There are some major uncertainties and data gaps in analyzing its environmental impact, including the size distribution and composition of particulates produced, ultimate fate of plume and plume constituents during the typical "coning aloft" pattern of plume behavior, and the extent to which HCl in plume could add to acid rain problems.

- Land-based incineration, although relatively more expensive, is suited for the disposal of other types of liquid wastes as well as sludges, solids, semi-solids, and contaminated containers, with no restraints on the minimum quantity accepted for disposal.

2. LAND-BASED INCINERATION

2.1 GENERAL DESCRIPTION

Land-based incineration is the predominant method for the disposal of organochlorine wastes in the United States at the present time. In the land-based incineration process, organochlorine wastes are destroyed by controlled oxidation at high temperatures, followed by efficient scrubbing of the furnace gas effluent to remove the hydrogen chloride formed. In addition to the incinerator and the scrubbing system, the basic components of a land-based incineration facility also include a stack for the dispersion of effluent gases, tank farm for the storage of wastes, a stabilization lagoon system for the treatment of wastewater generated from the scrubber system, and a landfill area for the disposal of incinerator ashes. Sludge from the wastewater treatment lagoon system will eventually be disposed of in an approved landfill area.

For the purpose of comparative cost analysis and environmental assessment, the facility operated by Rollins Environmental Services, Inc. and located at Houston, Texas was selected as the model representative of land-based incineration. This is a centralized incineration facility extensively used for the contract disposal of organochlorine wastes. A brief description of the Rollins incineration facility is provided in the following section.

2.1.1 The Rollins Incineration Facility

The Rollins incineration system consists of a rotary kiln and a liquid injection system, both feeding a common afterburner (Figure 1). The main burner is for liquid wastes only and is of the vortex horizontal type. The waste liquid burner flame temperature is approximately 1500°C. The rotary kiln, equipped with a second burner, is 4.9 meters long and 3.2 meters in diameter. Flame temperature in the kiln is normally 1300°C. The afterburner dimensions are: 10.6 meters overall length, 4.0 meters high, and 4.3 meters

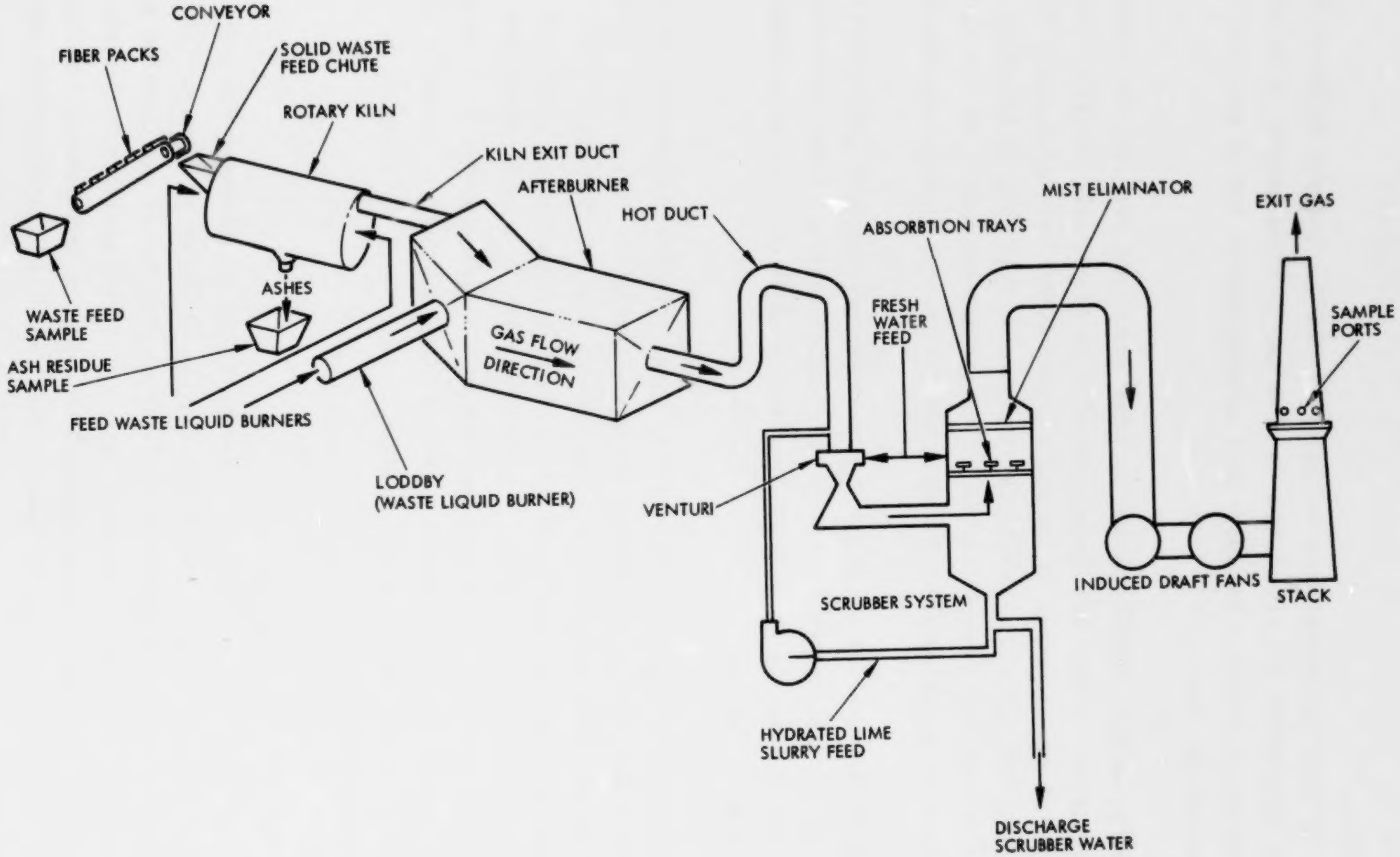
CONVEYOR
FIBER PACKS
SOLID WASTE FEED CHUTE
ROTARY KILN
KILN EXIT DUCT
AFTERBURNER
HOT DUCT
MIST ELIMINATOR
EXIT GAS
ABSORBTION TRAYS
FRESH WATER FEED
SAMPLE PORTS
ASHES
WASTE FEED SAMPLE
ASH RESIDUE SAMPLE
GAS FLOW DIRECTION
FEED WASTE LIQUID BURNERS
LODDBY (WASTE LIQUID BURNER)
VENTURI
INDUCED DRAFT FANS
STACK
SCRUBBER SYSTEM
HYDRATED LIME SLURRY FEED
DISCHARGE SCRUBBER WATER

Figure 1. Schematic of Rollins Environmental Services Incinerator

wide. Afterburner temperature is typically 1300°C. Overall retention time of the incinerator and afterburner is from two to three seconds at an average temperature of 1400°C. The total heat release rate is 100 GJ per hour (95 million Btu per hour).

Solid wastes, usually packed in fiber drums, are fed into the rotary kiln by a conveyor. Liquid and sludges may also be pumped into the kiln. Liquid wastes that can be burned in the waste liquid burner are fed directly from tanks into the burner. The maximum liquid waste feed rate to the waste liquid burner is 2.84 cubic meters per hour (750 gallons per hour), and the normal feed rate is approximately 2.27 cubic meters per hour (600 gallons per hour).

Both the kiln and the waste liquid burner are equipped with natural gas ignitors and gas burners for initial refractory heat-up, flame stability, and supplemental heat, if necessary. Supplemental heat can also be provided by burning No. 2 fuel oil.

As shown in Figure 1, the effluent gases from the incinerator are passed through a duct into a wet venturi scrubber, absorption trays, and a mist eliminator before entering the stack. The exhaust stack is 30 meters high. Lime is injected into the scrubber water to neutralize the hydrogen chloride absorbed. Used scrubber water, typically containing 10,000 ppm calcium and 10,000 ppm chlorides, is discharged into settling ponds where it is analyzed and further treated, if necessary, before final discharge. Sludge is allowed to settle in the ponds and will eventually be removed and disposed of in an approved landfill area.

2.2 COST ANALYSIS

Individual economic analyses were performed to determine the costs of disposal for five typical liquid organochlorine wastes at a centralized, contract land-based incineration facility similar to the one operated by Rollins Environmental Services at Houston, Texas. The five wastes selected for economic analyses included a perchloroethylene waste, a hexachlorocyclopentadiene waste, a mixed vinyl chloride monomer (VCM) and chlorinated solvent waste, a

VCM waste, and a waste produced during the manufacture of allyl chloride, epichlorohydrin, dichloroethane, and vinyl chloride (hereafter referred to as the combined manufacturing waste, or CMW). The mixed VCM and chlorinated solvent waste and the VCM waste were selected because both wastes are also suitable feedstocks for chlorolysis, and the disposal costs for these wastes by land-based incineration can be readily compared with the processing costs for these wastes by chlorolysis. The CMW waste was selected because the waste composition and physical properties are representative of the average of organochlorine wastes, and because the waste has been successfully burned on board the M/T Vulcanus. The perchloroethylene and hexachlorocyclopentadiene wastes were selected to examine the effects of chlorine content and heating value on the cost of disposal. As indicated by selected properties of the five organochlorine wastes given in Table 3, the perchloroethylene waste has a higher chlorine content and a lower heating value than the other organochlorine wastes.

The economic analyses performed were divided into capital investment cost, annual operating costs, and unit disposal costs.

2.2.1 Capital Investment

The capital investment cost for a centralized, land-based incineration facility to dispose of organochlorine wastes was estimated based on equipment cost data supplied by Rollins Environmental Services, Inc. The major equipment items at the Rollins facility include an incineration system rated at 100 GJ per hour, two feed pumps, two induced draft fans, a venturi scrubber, a Flexitray absorber, a 30 meter stack, tank farm for the storage of liquid wastes, a lime slurry tank, and a stabilization lagoon system. At an average liquid waste feed rate of 2.27 cubic meters per hour (600 gallons per hour), a total of 23,420 metric tons of organochlorine wastes could be incinerated at the Rollins facility per year, assuming that the incinerator operates at 330 days per year and 24 hours per day.

TABLE 3. ELEMENTAL COMPOSITION AND HEATING VALUE OF ORGANOCHLORINE WASTES

Waste Characteristics	CMW Waste*	Perchloro-ethylene Waste	Hexachloro-cyclopentadiene Waste	VCM & Solvent Waste	VCM Waste
Elemental Composition					
Carbon (wt %)	30.01	20.90	20.76	23.5	27.9
Hydrogen (wt %)	4.17	0.12	0.67	2.0	3.3
Nitrogen (wt %)	0.012	--	0.37	--	--
Sulfur (wt %)	0.009	--	0.02	--	--
Chlorine (wt %)	62.6	78.98	76.47	--	--
Oxygen (wt %)	3.20	--	1.71	74.4	68.7
Higher Heating Value†	16,166 kJ/kg (6,950 Btu/lb)	6,862 kJ/kg (2,950 Btu/lb)	10,002 kJ/kg (4,300 Btu/lb)	9,746 kJ/kg (4,190 Btu/lb)	12,351 kJ/kg (5,310 Btu/lb)

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[*] This waste was produced during the manufacture of allyl chloride, epichlorohydrin, dichloroethane, and vinyl chloride.

[†] The higher heating value or gross heating value of a substance is the heat evolved in its complete combustion under constant pressure at a temperature of 25°C when all the water initially present as liquid in the substance and that present in the combustion products are condensed to the liquid state. The net heating value is similarly defined, except that the final state of the water in the system after combustion is taken as vapor at 25°C.

Source: Properties of the CMW waste were obtained from Reference 4. Properties of the perchloroethylene waste were obtained from private communication of a chemical company to C. C. Shih. Properties of the hexachlorocyclopentadiene waste were obtained from Reference 5. Properties of the VCM and solvent waste and the VCM waste were obtained from Reference 3, except that heating values for these wastes were estimated from the heating values of the waste components.

In the estimation of the capital investment cost, the major equipment costs were adjusted to March 1978 basis using the Chemical Engineering Plant Cost Index. The costs of other portions of the incineration facility and associated labor costs were estimated using the method of Happel (Reference 6). Land prices are not included in the capital investment cost. The total capital investment cost for the land-based incineration facility, as presented in Table 4, is $4,592,600. Approximately 65 percent of the capital investment cost can be attributed to the installation cost for the incinerator.

2.2.2 Annual Operating Cost

The annual operating costs for the disposal of organochlorine wastes at a land-based incineration facility consist of the costs of operating labor, maintenance, utilities, overhead expenses, taxes and insurance, and hydrated lime. The operating labor costs were calculated based on the number of personnel assigned to operate the Rollins incineration facility and at labor rates for the Houston, Texas area. The maintenance costs were based on historical maintenance cost data furnished by Rollins Environmental Services, Inc. The utility cost includes the cost of electricity to operate the pumps and fans and the cost of supplementary fuel. The amount of No. 2 fuel oil needed was estimated from the heating value of the organochlorine waste fed. For the Rollins incinerator, a heating value of 18,600 kJ/kg (8,000 Btu/lb) is necessary to provide adequate heat release for either the waste or combination of waste plus auxiliary fuel. Supplementary fuel is therefore required for any organochlorine waste with heating value below 18,600 kJ/kg. The hydrated lime requirement was calculated based on the amount needed to neutralize the hydrogen chloride formed from the incineration of the organochlorine waste. Costs for overhead expenses and taxes and insurance have been included at rates prevalent in the chemical industry.

The annual operating costs for the disposal of 23,420 metric tons per year of the CMW waste at a land-based incineration facility is presented in Table 5. The net annual operating cost is $2,345,700. Because of the relatively high heating value of the CMW waste, the cost of fuel oil amounts to only $123,500 per year. For the disposal of other organochlorine wastes,

TABLE 4. CAPITAL INVESTMENT FOR A CENTRAL LAND-BASED INCINERATION FACILITY

Equipment	Size	Estimated Costs* Equipment	Estimated Costs* Labor	Total
1-Venturi scrubber, absorber, pumps and stack	5,300 lpm	$103,000		
2-Induced draft fans, including motors	300 KW each	80,000		
2-Feed pumps	1,300 lph each	5,100		
1-Tank farm, including lime slurry tank	3,040 cu.m.	133,000		
		$321,100	$ 32,100	
Instruments (10% of equipment)		32,100	4,800	
(Key Accounts)		$353,200	$ 36,900	
Insulation (10% of key accounts)		35,300	53,000	
Piping (45% of key accounts)		158,900	158,900	
Foundations (4% of key accounts)		14,100	21,200	
Buildings (4% of key accounts)		14,100	9,900	
Structures (4% of key accounts)		14,100	2,800	
Fire Protection (0.75% of key accounts)		2,600	16,900	
Electrical (4.5% of key accounts)		15,900	23,800	
Painting and Clean-up (0.75% of key accounts)		2,600	16,900	
Subtotal		$610,800	$340,300	$ 951,100
Installed Costs of Special Equipment				
1-Incinerator, conveyor fed	24 million Kcal/hr.			1,900,000
1-Stabilization lagoon system	30,000 cu.m.			93,000
Equipment and Labor				$2,944,000
Overheads (30% of Equipment & Labor)				883,200
Total Erected Cost				$3,827,200
Engineering Fee (10% of Erected Cost)				382,700
Contingency (10% of Erected Cost)				382,700
Total Capital Investment				$4,592,600

* March 1978 basis.

TABLE 5. ANNUAL OPERATING COST FOR DISPOSAL OF 23,420 METRIC TONS/YEAR OF A REPRESENTATIVE ORGANOCHLORINE WASTE AT A CENTRAL LAND-BASED INCINERATION FACILITY

Item	Cost, $/Year
Chemicals	
Hydrated lime: 24,520 metric tons @ $35.00/metric ton	$ 858,200
Utilities	
Electric power: 9,980,000 Kw-hr @ $0.015/Kw-hr	149,700
Fuel Oil: 9,500 bbl @ $13.00 per bbl	123,500
Operating Labor	
Operator, 3 men per shift, $8.65/manhour	226,700
Chief Operator, 1 man per shift, $12.12/manhour	105,900
Maintenance	
Maintenance labor, 4 men, $8.65/manhour	72,000
Maintenance supply	210,000
Contracted maintenance	91,000
Direct Overhead (30% of Operating Labor and Supervision)	99,800
General Plant Overhead (50% of Operating and Maintenance Labor and 3% of Total Plant Cost)	340,000
Taxes and Insurance (1.5% of Total Plant Cost)	68,900
Net Annual Operating Cost	$2,345,700

the costs of operating labor, maintenance, overhead expenses, taxes and insurance, and electric power would be the same as those for the Shell waste, whereas the costs of hydrated lime and fuel oil would be dependent on the chlorine content and heating value of the individual wastes. The effects of these variables on the cost of waste disposal are addressed in the next section.

2.2.3 Unit Disposal Cost

The method used for estimating the unit cost of disposal of organochlorine wastes is based on the discounted cash flow (DCF) technique. In essence, this technique determines the annual revenue during the plant life which will generate a discounted cash flow equal to the total capital invested for the plant. In DCF analysis, all future net income is discounted to a present value depending on the discounted cash flow rate of return (DCFRR). In other words, the DCFRR is the interest rate at which present value of all expenditures over the life of the plant is equal to the present value of revenue. Discounting can also be done on either an annual or continuous basis. For the present situation, it is more reasonable to assume that transactions will occur throughout the year and not in one lump sum, and therefore continuous discounting is more representative of the actual flow of funds. Plant life was assumed to be ten years.

The calculation of discounted cash flow for the disposal of 23,420 metric tons per year of the CMW waste at a land-based incineration facility is illustrated in Table 6. The calculation procedure follows that described by Uhl (Reference 7), and the assumptions used are discussed in detail in Appendix A. The calculation showed that at 15% DCFRR, an annual cash flow of $1,177,009 must be generated to offset the expenditures in capital investment, working capital and startup cost. As cash flow is the sum of the net profit and depreciation, the annual revenue that must be derived can be found from:

$$CF = D + (1 - t)(S - C - D)$$

where:

CF = Annual cash flow
D = Depreciation

TABLE 6. CALCULATION OF DISCOUNTED CASH FLOW FOR THE DISPOSAL OF THE CMW WASTE BY LAND-BASED INCINERATION AT 15% DISCOUNTED CASH FLOW RATE OF RETURN.

Time, Year	Item	Investment	Cash Flow	Discounting Factor	Discounted Cash Flow
-2 to 0	Depreciable Investment	$4,592,600		1.1662	- $5,355,871
0	Working Capital	$ 636,069		1.0	- $ 636,069
1	Interest on 30% of Total Plant Cost at 10% Rate		- 0.5* ($307,796)	0.9048	- $ 139,253
0 to 2	Startup Cost		- 0.5* ($229,630)	0.9286	- $ 106,619
0 to 10	Cash Flow		10 ($1,177,009)	0.5179	$6,095,886
10	Recover Working Capital	- $ 636,069		0.2231	$ 141,926
					0

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* The actual cash flow for these two items are reduced by 50% due to the effect on cash flow of income tax.

S = Annual revenue
C = Net annual operating cost
t = Income tax rate

Assuming 10 year straight time depreciation and an income tax rate of 50%, the annual revenue that must be generated was calculated to be \$4,240,488. For land-based incineration, no saleable products are generated and the annual revenue is derived completely from waste disposal charges. The unit disposal cost was therefore obtained by dividing the annual revenue by the annual quantity of waste requiring disposal. For the **CMW** waste, the unit disposal cost was calculated to be \$181.06 per metric ton.

To facilitate the computation of unit disposal costs for other organochlorine wastes, a general unit disposal cost equation has been derived based on Uhl's economic evaluation procedure (Reference 7). The derivation of the unit disposal cost equation and the assumptions involved are described in Appendix A. The unit disposal cost equation is given as:

$$\text{Unit Disposal Cost (\$/metric ton)} = \frac{C + aI + bW + cU - S'}{G}$$

where:

a, b, c are constants depending on the discounted cash flow rate of return and given in Table A-2.
C = Net annual operating cost, \$;
I = Total plant investment, \$;
W = Working capital, \$;
U = Startup cost, \$;
S' = Annual revenue received from the sale of products generated from the processing of wastes, \$;
G = Annual quantity of waste disposed, metric tons.

The unit disposal costs for the five organochlorine wastes at 15% DCFRR, as given in Table 7, range from \$181 to \$212 per metric ton. The higher unit disposal cost for the perchloroethylene waste is the result of its higher chlorine content and lower heating value. The hydrated lime requirement is directly proportional to the chlorine content of the organochlorine waste and was calculated from the reaction:

$$2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O.$$

TABLE 7. UNIT DISPOSAL COST FOR ORGANOCHLORINE WASTES AT A CENTRAL LAND-BASED INCINERATION FACILITY

Item	$/Metric Ton Waste				
	CMW Waste*	Perchloro-ethylene Waste	Hexachloro-cyclopentadiene Waste	VCM & Solvent Waste	VCM Waste
Operating Cost					
Hydrated lime	36.64	46.22	44.76	43.55	40.22
Electric power	6.39	6.39	6.39	6.39	6.39
Fuel Oil	5.27	25.34	18.57	19.12	13.50
Operating labor	14.20	14.20	14.20	14.20	14.20
Maintenance	15.93	15.93	15.93	15.93	15.93
Overhead expense	18.78	18.78	18.78	18.78	18.78
Taxes and insurance	2.94	2.94	2.94	2.94	2.94
Subtotal	100.15	129.80	121.57	120.91	111.96
Capital investment related items†	71.00	71.00	71.00	71.00	71.00
Working capital†	8.15	9.54	9.15	9.12	8.70
Startup cost†	1.76	1.76	1.76	1.76	1.76
Unit Disposal Cost	181.06	212.10	203.48	202.79	193.42

* This waste was produced during the manufacture of allyl chloride, epichlorohydrin, dichloroethane, and vinyl chloride.

† The charges of capital investment related items, working capital and startup cost to the unit disposal cost are based on 15% discounted cash flow rate of return.

With the assumption that all the chlorine present in the organochlorine waste is converted to hydrogen chloride, the hydrated lime requirement, at 60% in excess of the stoichiometric amount, is given as:

Hydrated lime requirement = 1.672 X weight % Chlorine/100.
(Metric ton/metric ton waste)

Thus, a 10% difference in the chlorine content of wastes would result in a $5.85 difference in the unit disposal cost of these wastes.

The supplementary fuel requirement for land-based incineration was calculated from the heating value of the organochlorine waste. As indicated in Table 7, the fuel cost for the disposal of the CMW waste amounts to only $5.27 per metric ton, or less than 3% of the unit disposal cost. On the other hand, the fuel cost for the disposal of the perchloroethylene waste amounts to $25.34 per metric ton, or 11.9% of the unit disposal cost. Most organochlorine wastes have higher heating values in the 9,300 to 14,000 kJ/kg (4,000 to 6,000 Btu/lb) range, and the fuel cost for disposal would be from $10.00 to $20.00 per metric ton of waste. For wastes with known chemical composition, the heating value can be estimated from its carbon, hydrogen, oxygen and chlorine content by using the method of Handrick (Reference 8). For two wastes with components of the same structural group (e.g., straight-chain hydrocarbons), the higher chlorine content waste would also have the lower heating value. Thus, organochlorine wastes of high chlorine content generally have low heating values, and the unit disposal cost for these wastes would be higher due to both the costs of hydrated lime and supplementary fuel.

The effect of discounted cash flow rate of return on the unit disposal cost of organochlorine wastes by land-based incineration is summarized in Table 8. At 10% DCFRR, the unit disposal cost would be approximately $24 per metric ton lower than at 15% DCFRR. At 20% DCFRR, the unit disposal cost would be approximately $29 per metric ton higher than at 15% DCFRR.

The unit disposal costs for organochlorine wastes calculated using the cost model described in this study can also be compared with the actual costs charged by contract waste disposal companies. According to Rollins

TABLE 8. EFFECT OF DISCOUNTED CASH FLOW RATE OF RETURN (DCFRR) ON UNIT DISPOSAL COST OF ORGANOCHLORINE WASTES BY LAND-BASED INCINERATION

DCFRR	$/Metric Ton Waste				
	CMW Waste	Perchloroethylene Waste	Hexachlorocyclopentadiene Waste	VCM & Solvent Waste	VCM Waste
10%	157.31	187.87	179.38	178.70	169.47
12%	166.28	197.03	188.49	187.80	178.52
15%	181.06	212.10	203.48	202.79	193.42
18%	197.52	228.85	220.15	219.45	209.99
20%	209.46	241.00	232.24	231.54	222.01

Environmental Services, the unit disposal costs for the CMW waste and the perchloroethylene waste would be $183 per metric ton ($0.90 per gallon) and $215 per metric ton ($1.30 per gallon), respectively. These costs are in good agreement with the calculated unit disposal costs of $181 per metric ton and $212 per metric ton for the same two wastes, at 15% DCFRR. For the disposal of liquid polychlorinated biphenyl (PCB) wastes, Chem-Trol Pollution Services, Inc. of Model City, New York, quoted a unit disposal cost of $220 per metric ton. Liquid PCB wastes have an average chlorine content of approximately 45 weight percent and a low heating value similar to that of the perchloroethylene waste. At 15% DCFRR, the unit disposal cost for liquid PCB wastes was calculated to be approximately $205 per metric ton. This again shows that the cost of disposal of organochlorine wastes at a land-based incineration facility can be calculated with accuracy using the cost model described in this study, and by assuming 15% DCFRR.

The unit cost for contract disposal of organochlorine wastes at a centralized land-based incineration facility is not a function of waste volume, as long as the volume of waste requiring disposal each time is a minimum of a tank truck. In the calculation of the unit disposal cost, the capital charges and operating expenses can be simply prorated to the different organochlorine wastes disposed during the year. In other words, the unit disposal cost is based on the disposal of a total of 23,420 metric tons of organochlorine wastes per year, and not on the disposal of large quantities of a specific organochlorine waste.

2.3 ENVIRONMENTAL ASSESSMENT

In order to determine the environmental impact of land-based incineration activities, analyses were performed to estimate the effect these activities could have on air and water quality. Gaussian diffusion and transport models were used to simulate the air quality expected changes and calculations were made to characterize scrubber wastewater. A detailed description of the simulation analysis is presented in Appendix B.

Air quality simulations were based on emissions and other data obtained at an incineration facility considered to be representative of a modern U.S. commercial disposal facility capable of accepting organochlorine wastes. (See Section 2.1 for a description of the incinerator and scrubbing system). Major input parameters to the simulation model consist of effective stack height (or plume rise), wind speed and stability category.

Plant operation parameters and characteristics were used to derive effective stack height. Meteorological parameters (wind speed and stability category) considered to be representative of conditions at a Houston site were chosen. A wind speed of 4.0 meters/second and "D" atmospheric stability category were used. It was assumed that all plume constituents remain airborne with no identifiable sinks at the ground level.

No data were available describing emissions from the incineration of strictly defined organochlorine materials at a land-based facility. However, incineration tests had been performed on nitrochlorobenzene (NCB) at a representative facility. Emissions obtained during these tests were used for the air quality simulations for HCl, particulates and trace metals. Emission rates for the unburned waste were estimated, based on the destruction efficiency (>99.999%) achieved during the NCB burn, and a typical organochlorine waste feed rate of 3 metric tons/hour (Reference 9). For the air simulation analysis, however, it was assumed that 0.01% of the waste feed was emitted as uncombusted material. Thus, results are conservative by at least a factor of 10. Emissions used in air quality simulation are listed in Table 9. These emissions should be representative of those generated from the incineration of a typical organochlorine waste.

Characterization of scrubber water was derived for emissions resulting from the incineration of the CMW waste, which has a chlorine content of 62.6 weight percent. The scrubber solution used was assumed to be 3,200 liters per minute of scrubber water and a 32% $Ca(OH)_2$ solution. At 60% in excess of the stoichiometric requirement, the amount of lime slurry needed was calculated to be 193 liters per minute. Total discharges of chlorides and calcium were estimated to be 1,880 kg per hour and 1,740 kg per hour, respectively.

TABLE 9. STACK EMISSIONS USED FOR LAND-BASED AIR QUALITY SIMULATION (ALL RATES IN Kg/Hr)

HCl	Particulates	Trace Metals, Each	Unburned Wastes
0.895	1.03	0.00069	0.3

Notes:
1) Emission rates for HCl, particulates, trace metals, and unburned wastes are all based on a dry volumetric flow rate of 68877 m^3/hr. Concentrations of HCl, particulate and trace metals in the stack gases are 13 mg/m^3, 15 mg/m^3 and 0.01 mg/m^3, respectively.
2) Trace metals include Ti, Ni and Cr, each at the listed concentration level. These concentrations are based on analysis of the waste and not on stack gas measurements.
3) Emission estimates for unburned wastes were based on a 99.99% destruction efficiency and a hypothetical waste feed rate of 3 metric tons/hr considered to be the average feed rate for CMW waste at one of the largest U.S. incinerator.

Selected air quality simulation and wastewater characterization results for land-based incineration activities are presented in Table 10. Air quality data presented are the maximum ground level concentrations for stated meteorological conditions. Complete results of air quality simulations (Appendix B) give predicted ground level concentrations at various distances downwind from the source. The maximum shown in Table 10 are predicted to occur 3,000 meters from the source.

The maximum HCl concentration is 536.6 nanograms/cubic meter or 0.0004 ppm. This is four orders of magnitude less than the TLV of 5 ppm. This concentration is also lower than the sensory threshold levels reported in the literature (0.067 ppm) and is not known to have any adverse effects (Reference 12). The most stringent of the National Ambient Air Quality Standards (NAAQS) for particulates (60 $\mu g/m^3$ - annual geometric mean) is an order of magnitude larger than the maximum predicted total particulate concentration.

TABLE 10. SUMMARY OF AIR AND WATER QUALITY EFFECTS ASSOCIATED WITH LAND-BASED INCINERATION

Air Quality[a]				Scrubber Water Quality[b] (mg/liter)		
HCl ng/m^3	Particulates ng/m^3	Unburned Wastes ng/m^3	Trace Metals ng/m^3	CMW Waste with 62.6% Chlorine[c]		
				Cl^-	Ca^{++}	TDS
536.6	617.6	179.9	0.41	12,300	11,420	23,720

(a) Maxima from air quality simulations: effective stack height - 96.5 meters, wind speed - 4.0 meters/second, ground surface reflectivity = 1.0 and atmosphere stability = D. These maxima occur 3,000 meters downwind from the source.

(b) TDS levels of scrubber water depend primarily on percentage chlorine composition of the incoming wastes and type of scrubber solution used. Concentrations in mg/liter.

(c) Scrubber solution is 32% $Ca(OH)_2$.

It should also be stressed that tests showed no emission of unburned wastes from the stack, and the emissions rate used in the model was based on a 99.99% destruction efficiency. The calculated destruction efficiency, based on the detection limit of analytical instrumentation, was 99.999%. Therefore, the predicted concentrations of unburned wastes are conservative.

Water quality impacts will be reflected in the need for additional downstream treatment and in possible adverse effects of heavy metals and high TDS. Possible adverse effects include direct impacts on treatment plant processes (e.g., process upsets and/or receiving water bodies if these materials were not removed by the treatment process), and indirect effects of any trace metals or unburned waste that might be associated with the sludges resulting from treatment.

All effluent streams (stack gas, spent scrubbing solution, sludge, clinker, bottom ash, and treated scrubbing solution) have the potential of adversely affecting the soil. Impacts on the soil can be manifested in several ways, ranging from no adverse effects to contamination of the soil, vegetation, and groundwater.

The combustion products which are entrained in the stack gases will eventually be removed from the atmosphere, as previously discussed, and will come into contact with the soil or surface water. The effects and interactions of these contaminants with surface water has been previously discussed, and their interaction with the soil will be addressed in the discussion of residue handling.

Clinker and any bottom ash formed will contain primarily inorganic carbonaceous compounds. Less than 3% of the total weight of carbonaceous compounds will be trace compounds, including heavy metals. Because of the presence of these heavy metals, these solids should be disposed of in landfills approved for hazardous wastes.

Spent scrubbing solution, if sent to an on-site settling tank or pond, will generate two streams. One stream will be the clear liquid effluent which may be suitable for sending to municipal treatment facilities. The other stream will be sludge or solid residue from the settling process, which, because it will contain heavy metals and perhaps some organics, should be disposed of in an approved landfill.

Spent scrubber solution may not be treated on-site, but rather disposed of directly into the municipal sewage system. This will result in sludges generated by the municipal treatment process containing heavy metal contaminants which will be landfilled and, depending on the destruction efficiency of the incinerator, the liquid effluents could potentially contain small amounts of organochlorine wastes. However, if destruction efficiencies are kept at the levels achieved on test burns, (it is expected that regulatory controls will ensure that is the case), no unburned wastes will be expected in the scrubber wastewater.

Effects of the contaminants once deposited onto or into the soil vary as a function of the type and porosity of the soil, the weather conditions, and the mobility of the individual contaminants (Reference 13). Some contaminants, for example, selenium ($HSeO_4^-$ & $SeO_3^=$), are relatively mobile in the soil, while metal cations, for example, iron (Fe^{++}), zinc (Zn^{++}), lead (Pb^{++}), and copper (Cu^{++}) are moderately mobile in the soil.

The magnitude of any of these effects cannot be determined accurately using available data. If the concentration of heavy metals and unburned wastes in waste scrubber water is found to be too high, then additional treatment may be required. If these high concentrations are found in wastewater treatment sludges, then the chosen disposal method for the solids will have to ensure that air and water resources are not contaminated.

Malfunction Potential

The functional analysis of an incineration facility for a land-based operation indicates that most components of the system are in a "series" configuration; each series component must be adequately functioning to avoid degraded performance. A few process components may be in a "parallel" configuration, allowing a switch-over to another component upon detection of problems with the on-stream component. Waste feed line filters will usually have two or more units in parallel, and even feed pumps may be "spared" (duplicated) if plant processing rates are determined to be especially critical. Multiple burners in an incinerator are not considered to be redundant components, because the loss of any burner will result in degraded performance. Waste feed and wastewater spills and leaks can be caused by material corrosion, valve packing and pump seal deterioration, liquid level control failure, or manual errors.

A listing of some possible operational malfunctions at a land-based incineration facility is given in Table 11. The largest hazardous spill possibility exists in the storage tank and transfer area. All of this area in a facility should be paved, diked, and drained to a catch basin with pumped return to the storage tanks. Absorbent material should be ready to use for clean-up in the event of a leak or failure in other parts of the system.

The other major failure cause could come from incinerator malfunctions, such as burner flameout, leading to a toxic vapor discharge. Well-designed combustion controls provide a large amount of protection against these potential problems.

TABLE 11. POTENTIAL OPERATIONAL MALFUNCTIONS AT A LAND-BASED INCINERATION FACILITY

Operation	Possible Malfunction	Consequence
Tank Filling	1. Overfill on level intelock failure	Waste spill
	2. Leakage due to pump seal, valve packing material corrosion, etc.	Small waste spill
	3. Inclusion of unauthorized waste by subversion of quality control procedures	Possible incineration difficulties
Waste Transfer through Pump and Filter	1. Leakage due to pump seal, material corrosion, etc.	Small waste spill
	2. Filter plugging	None if filters switched on high pump discharge pressure measurement
Waste Injection to Incinerator	1. Nozzle plugging (low flow detection)	Temporary shut-down
	2. Atomization air loss on air blower failure	Failure to combust, toxic vapor discharge, liquid accumulation
Incineration	1. Burner flame loss (flame-out) due to loss of fuel pressure, loss of primary combustion air, coking, or water slug in feed	Transient toxic vapor discharge prior to automatic shutdown on flame loss detection (or low combustion temperature. A water layer in the tank can be isolated by conductivity measurement interlock to the waste feed pump)
	2. Improper fuel rate	Excess waste product in discharge
	3. Improper air/fuel ratio	Inefficient combustion
	4. Injection into a cool combustion zone on startup	Inefficient combustion
Stack Gas Scrubbing	1. Scrubbing solution circulating pump fails	High HCl concentration in stack gases
	2. Weak scrubbing solution	Not much change, even water scrubbing is very effective for HCl removal
	3. Pump, valve, or tank leaks	Scrubbing solution spill (no consequence if water is used for scrubbing)
Wastewater Treatment	1. Chemical addition pump fails	Low pH discharge
	2. Pump, valve, or tank leaks	Small wastewater spill

3. AT-SEA INCINERATION

3.1 GENERAL DESCRIPTION

Incineration of combustible chemical wastes on board specially designed vessels has been practiced off European coasts since 1971. This technology for disposal of toxic chemical wastes was demonstrated off U.S. coasts for the first time between October 1974 and February 1975, sanctioned by a permit granted by the U.S. Environmental Protection Agency (EPA) under the authority of the Marine Protection, Research, and Sanctuaries Act of 1972, as amended. A total of 16,800 metric tons of organochlorine wastes were incinerated during this first series of burns. The organochlorine wastes disposed were produced during the manufacture of allyl chloride, epichlorohydrin, dichloroethane, and vinyl chloride monomer at Shell Chemical Company's Deer Park, Texas plant.

A second incineration program, again burning organochlorine wastes from Shell Chemical Company's Deer Park, Texas plant, took place in March and April 1977 under U.S. EPA Special Permit No. 750D008E. The burn zone was located in the Gulf of Mexico and 18,000 metric tons of organochlorine wastes were incinerated. A third burn started in July and ended in September 1977 in a Pacific Ocean burn zone west of Johnston Atoll where 10,400 metric tons of U.S. Air Force stocks of Herbicide Orange were incinerated under U.S. EPA Research and Special Permits No. 770DH001R and 770DH001S.

In all three U.S. programs, wastes were burned on board the M/T Vulcanus, owned by Ocean Combustion Services, B.V., of the Netherlands. A brief description of the M/T Vulcanus is provided in the following section.

3.1.1 The M/T Vulcanus

The M/T Vulcanus, originally a cargo ship, was converted in 1972 to a chemical tanker fitted with two large incinerators at the stern. The double hull vessel meets all applicable requirements of the Inter-governmental Maritime Consultative Organization (IMCO) concerning transport of dangerous cargo by tanker. Her crew numbers 18; twelve to operate the vessel and six to operate the incinerators. Two diesel engines drive the single propeller to give cruising speeds of 10 to 13 knots. Waste is carried in 15 tanks, the walls and bottoms of which form the inner hull and bottom. The space between the two hulls is used for ballast. Ballast tanks may be filled with sea water and emptied independently as required to trim and balance the ship. Tanks range in size from 115 to 574 cubic meters, with an overall waste capacity of 3503 cubic meters. Filling of tanks is accomplished through a manifold on deck using a dockside loading pump. During normal operation the waste tanks can be discharged only through the incinerator feed system. There is, however, provision for discharging the cargo into the ocean if an emergency arises that requires protection of the crew. Information applicable to the M/T Vulcanus is given in Table 12.

Waste is burned on board the M/T Vulcanus in two identical, refractory-lined furnaces located at the stern. Each incinerator consist of two main sections, a combustion chamber and a stack, through which the combusting gases pass sequentially. This dual chamber configuration, which is characteristic of most high intensity combustion systems, uses the first chamber for internal mixing and initial combustion and the second for adequate residence time and to complete combustion.

Combustion air is supplied by large fixed speed blowers with a rated maximum capacity of 90,000 cubic meters per hour for each incinerator. Adjustable vanes are incorporated in the combustion air supply system to control air feed rate. They are normally left fully open, however, no instrumentation to monitor air volumetric flow is installed.

Liquid wastes are fed to the combustion system by means of electrically driven pumps. Upstream of each burner supply pump is a device (Gorator) for reducing solids in the waste to a pumpable slurry. The Gorator also acts as a mixing pump by recirculating waste to the cargo tanks.

TABLE 12. M/T VULCANUS, GENERAL INFORMATION

Length overall, m	101.95
Breadth, m	14.40
Draft, maximum, m	7.40
Deadweight (DWT), metric tons	4,768
Speed, knots	10-13
Tank capacity, m^3	3,503
Number of tanks	15, from 115 to 574 m^3
Tank coating	No coating in tanks, pipes, pumps, etc. All equipment consists of low carbon steel
Loading equipment	Not available, but can be placed on board, if required
Hose connection, diameter, cm	10.2, 15.2, and 20.3
Safety equipment	Specially designed for this task and in accordance with latest regulations of IMCO, Scheepvaart-Inspectie (The Hague)
Waste to be processed	Must be liquid and pumpable. May contain solid substances in pieces up to 5 centimeters in size. Must not attack mild steel
Incinerators	2
Per incinerator:	
Overall height, m	10.45
Combustion chamber	
OD, m	5.5
ID, m	4.8
Stack (top)	
OD, m	3.8
ID, m	3.4
Waste feed (max), metric tons/hr	12.5
Combustion air (max), m^3/hr	90,000
Burners (Vortex type)	3
Volume, m^3	120
Residence time, sec	1.0 at 1500°C (calculated)

Three vortex-type burners are located at the same level on the periphery of each furnace near its base. They are of a rotating cup, concentric design and deliver waste or fuel oil through a central tube to an atomization nozzle, where it meets high velocity air delivered through an annulus. Three-way valves on each incinerator burner provide either waste feed, fuel oil feed, or a shutoff condition. Waste and fuel oil cannot be valved into a burner simultaneously; however, alternate burners could be operated with fuel and waste to achieve higher combustion temperatures if necessary, depending on the relative heat contents of the fuel oil and waste.

3.2 COST ANALYSIS

For at-sea incineration of organochlorine wastes, definitive cost data are not available at the present time to estimate capital investment cost and annual operating costs with accuracy. The discussion on cost of disposal is, therefore, mostly based on prices charged by Ocean Combustion Services, B.V. and SBB Stahl-Und Blech-Bau Ltd.

3.2.1 Capital Investment

Under contract to the Maritime Administration of the U.S. Department of Commerce, Global Marine Development Inc. of Newport Beach, California is currently (July 1978) conducting a program titled "A Study of the Economics and Environmental Viability of a U.S. Flag Toxic Chemical Incineration Ship". As part of this ongoing study, preliminary estimates for the capital investment cost of modifying a World War II T2 tanker to an at-sea incineration vessel have been obtained. For a 150 meter (500 ft) long ship capable of loading 12,000 metric tons of toxic chemical waste, and equipped with six incinerators (five to be operated simultaneously and one as standby) with a combined burn rate of 95 metric tons per hour, Global Marine estimated that the capital investment cost would be $10.4 million. The M/T Vulcanus has a load capacity about one-third that of the Global Marine design, and the capital investment cost would probably be in the $4 million to $6 million range.

3.2.2 Annual Operating Cost

The annual operating costs for at-sea incineration of organochlorine wastes consist of the costs of operating crew, maintenance, fuel for the ship and for waste incineration, overhead expenses, and taxes and insurance. For the incineration ship in the Global Marine study, preliminary estimates have indicated that the net annual operating cost would be $9.8 million. The net annual operating cost was computed with the following assumptions:

- 2 weeks per year for ship maintenance and repair.
- A utilization factor of 75% for the remaining 50 weeks per year, i.e., the incineration ship would either be burning wastes, or in transit to pick up wastes or to reach the burn zone, or in the process of waste loading for 6,300 hours per year.
- Disposal of 350,000 metric tons of waste per year. This is equivalent to incinerator operating time of 3,684 hours per year.

Details on the breakdown of the operating costs are not available from Global Marine at the present time.

3.2.3 Unit Disposal Cost

For disposal of organochlorine wastes on board the M/T Vulcanus, Ocean Combustion Services, B.V. quoted a March 1978 price of 175 Dutch Gilders per metric ton of waste. With an exchange rate of 1 Dutch Gilder = 0.4598 U.S.$, the unit disposal cost is U.S.$80.47 per metric ton of waste. For organochlorine wastes with heating values below 11,720 kJ/kg (5,040 Btu/lb), there is an additional fuel surcharge. To bring the M/T Vulcanus from Europe to the United States, the minimum quantity of waste requiring disposal would be two shiploads, or approximately 8,200 metric tons. A discount of 5 to 10% is allowed if the quantity of waste to be disposed is in excess of two shiploads. The M/T Vulcanus is also available for charter at 35,000 Dutch Gilders (U.S.$16,100) per day.

The charter cost for the M/T Vulcanus was slightly lower in 1977. For the disposal of 10,400 metric tons of Herbicide Orange, the U.S. Air Force paid a charter rate of $13,500 per day when not burning, and $15,000 per day during incineration. The total charter cost for the Herbicide Orange incineration program was approximately $2.6 million, or $250 per metric ton of waste. For this specific case, the unit disposal cost was considerably higher because of the remoteness of the burn zone, special preparations required in the handling of the Herbicide Orange, and contingency planning. The total burn time was 714 hours, or approximately 30 days (Reference 15). Thus, the cost associated with the actual burn was only $450,000. More than 80 percent of the total cost of disposal was due to demurrage charges for travelling to Gulfport, Mississippi, and then to Johnston Atoll in the Pacific Ocean and back to Europe. However, some savings was achieved because the empty Vulcanus was in the Gulf area at the time and did not have to travel all the way from Europe.

The Matthias III, owned by SBB Stahl-Und Blech-Bau Ltd., is not in active service. As of March 1978, however, price quotes for the disposal of liquid organochlorine wastes were available. The disposal cost for liquid organochlorine wastes on board the Matthias III was given as follows:

Waste Volume	Disposal Cost (f.o.b.)
<5,000 metric tons per year	$75 per metric ton
5,001 to 10,000 metric tons per year	$65 per metric ton
10,001 to 40,000 metric tons per year	$50 per metric ton
>40,000 metric tons per year	$45 per metric ton

These costs were comparable to the disposal costs charged by Ocean Combustion Services, B.V.

For the five typical liquid organochlorine wastes selected for cost analysis for land-based incineration, the unit disposal costs by at-sea incineration are given in Table 13. These unit disposal costs are based on prices charged by Ocean Combustion Services, B.V., and a fuel surcharge of $2.16 per GJ (equivalent to $13.00 per barrel) has been added to wastes with heating values below 11,720 kJ/kg (5,040 Btu/lb).

TABLE 13. UNIT DISPOSAL COST FOR ORGANOCHLORINE WASTES BY AT-SEA INCINERATION

Waste Type	Unit Disposal Cost, $/Metric Ton Waste
CMW Waste	80.47
Perchloroethylene Waste	90.96
Hexachlorocyclopentadiene Waste	84.18
VCM & Solvent Waste	84.73
VCM Waste	80.47

The unit disposal cost for organochlorine wastes by at-sea incineration can also be calculated using the preliminary capital investment cost and net annual operating cost figures provided by Global Marine. Assuming 10 year straight line depreciation and an income tax rate of 50%, the unit disposal cost for organochlorine wastes using the Global Marine incineration ship was calculated to be $40.86 per metric ton, at 15% DCFRR. This unit disposal cost is much lower than that for the M/T Vulcanus because of the larger loading capacity of the ship, the higher burning rate of the shipboard incinerators, and the assumption of a high utilization factor. The quantity of waste to be disposed per year on board the Global Marine incineration ship was assumed to be 350,000 metric tons, which represents 74 percent of the total estimated organochlorine wastes produced in the United States in 1978. Other types of liquid organic wastes as well as aqueous wastes contaminated with organics could also be disposed of by shipboard incineration. The portion of chemical wastes that are potential candidates for at-sea incineration could thus be several times that of the liquid organochlorine wastes requiring disposal.

Because of the preliminary nature of the Global Marine cost estimates, the unit disposal costs based on prices charged by Ocean Combustion Services, B.V. will be used for cost comparison purposes.

3.3 ENVIRONMENTAL ASSESSMENT

Analysis of environmental impacts for at-sea incineration activities were based on the results of models used to estimate effects of plume constituents on air and ocean water quality. Details of the air quality simulations are presented in Appendix B.

Major input parameters for air quality simulation are effective stack height (or plume rise), wind speed, and stability category. Values for these parameters selected for use in simulators are considered to be generally representative of conditions likely to occur under real world circumstances. In general, simulations were based on information obtained in connection with the incineration of CMW wastes on board the M/T Vulcanus in March 1977 (Reference 4). Effective stack height calculations were based on data obtained during this burn. The wind speed and atmospheric stability category used were selected after review of measured and statistical data for shore locations in the general vicinity of a burn zone located off the Gulf Coast. (Measured wind speed data are not available for the proposed off-shore site, therefore, data from the nearest shore-based meteorological stations were used instead.)

Wind speed (i.e., speed of the diffusing layer) is an input parameter which significantly influences predicted downwind pollutant concentrations. Generally, increasing wind speed decreases downwind concentration. When an incinerator ship is moving, the relative wind speed, as measured at the stack, may be greater than the speed of the diffusing layer. However, relative wind speed was not used as an input to the diffusion modeling performed here. This is because the materials emitted will assume the average speed of the diffusing layer shortly after they are discharged to the atmosphere. One result of this is that downwind concentrations near the source may be lower (due to the additional mechanical turbulence from the ship velocity) than estimated in this study. Downwind concentrations will also tend to be decreased by the fact that a moving source distributes its emissions into a larger volume of air per unit time (i.e., if the relative wind speed is greater than that of the diffusing layer).

The diffusion model employed assumed that the chemical species emitted remain airborne and are not removed from the atmosphere by either chemical or physical processes. There are a variety of technical arguments against this assumption. For example, particulate matter will be removed by gravity, and there will undoubtedly be acid-base interactions between airborne droplets of ocean water and HCl. However, the data required to take pollutant-marine boundry layer interactions into account is unavailable.

Wastes processed during the M/T Vulcanus burn were produced from the manufacture of allyl chloride, epichlorohydrin, dichloroethane and vinyl chloride (the CMW waste). Composition of the waste is given in Table 14. Elemental analysis of a typical organochlorine waste is shown in Table 15.

Emission rates used for the at-sea incineration are shown in Tables 16 and 17. These estimates were made assuming feed rate and emissions characteristics of the M/T Vulcanus furnaces. Emissions data for particulates were not obtained during the March 1977 burn. However, data were available describing waste composition and emissions of various inorganic constituents. These data were converted to mass emission rates and summed in order to derive an estimate of expected particulate emissions. The "summed inorganics" column of Table 17 presents the results of this derivation. It should be noted that these results compare favorably with the analysis data indicating a loss on ignition value of 99.8% for the CMW waste (Reference 4).

Estimation of the effects of at-sea incineration on ocean water quality were generally obtained by using a diffusion model to identify the ocean area affected by the incinerator's plume and determination of the water concentrations of plume constituents. The concentrations were determined by assuming that all of the material in the plume dissolved in a prescribed depth of the affected water area.

Selected air quality simulation and water quality effects for at-sea incineration activities are presented in Table 18. Air quality data represent maximum sea level concentrations. Complete air quality simulation results

TABLE 14. ANALYSIS OF ORGANOCHLORINE WASTE BURNED AT-SEA
(The CMW Waste)

● Physical Characteristics:	Loss on ignition, %	99.8
	Gross Thermal Content, Btu/lb	6,950
	Specific Gravity	1.28
● Elemental Analysis:	Element	Composition, %
	Carbon	30.01
	Hydrogen	4.17
	Nitrogen	0.012
	Sulfur	0.009
	Halogens as chlorine	62.60
● Other Constituents	Element	Concentration, ppm
	Si	>500
	P	50 - 500
	Ti	50 - 500
	Ca	>25
	Br	Trace
● Organic Composition:	Compound	Est. Conc. (% w/W)
	1,2,3-Trichloropropane	18
	Dichloropropenes (3)	11
	Dichloropropane	18
	Trichloroethane	12
	1,2-Dichloroethane	10
	1,1-Dichloroethane	0.9
	Dichloropropanol	6.2
	Chloropropene (Allyl Chloride)	5.7
	Chloropropanes (2)	5.8
	Chloroethane	0.6
	Trichloromethane (Chloroform)	0.5
	Tetrachlorobutenes (2)	2.4
	Acrolein (Propenal)	0.2
	Chlorobenzene	3.3
	Bis(2-Chloroethylether)	1.9
	Unidentified Chloro- and Oxychloro-Compounds	3
	Water	0.5

Source: Reference 4

TABLE 15. ELEMENTAL ANALYSIS OF CMW WASTE.

	BURN 1	BURN II
	% by weight	
Carbon	29	29.3
Hydrogen	4	4.1
Oxygen	4	3.7
Chlorine	63	63.5
	(Parts per million)	
Copper	0.51	1.1
Chromium	0.33	0.1
Nickel	0.25	0.3
Zinc	0.14	0.3
Lead	0.05	0.06
Cadmium	0.0014	0.001
Arsenic	<0.01	<0.01
Mercury	<0.001	<0.002

Source: Reference 16.

TABLE 16. EMISSION RATES USED FOR AT-SEA AIR QUALITY SIMULATION: HCl AND UNBURNED WASTES

Average Waste Feed Rate	Destruction Efficiencies, %	Emissions Rate, gm/hr	
		HCl	Unburned Wastes
22 metric tons/hr ($22X10^6$ gm/hr)	99.99 (max. observed)	$14.16X10^6$	$2.2X10^3$
	99.96 (min. observed)	$14.16X10^6$	$8.8X10^3$

Notes: 1) Data are for both furnaces of the M/T Vulcanus.

2) HCl emission rate assumes a 62.6% chlorine content in the waste, and a volumetric flow rate of 8700 Nm^3/hr of HCl is discharged from both stacks.

TABLE 17. EMISSION RATES USED FOR AT-SEA AIR QUALITY SIMULATION: INORGANICS (All units in kg/hr)

Summed Inorganics		Specific Elemental Constituents					
Low	High	Cu/Zn	As/Co	Pb/Ti	Ni	Cr	F
53	72	0.7	0.1	0.4	2	4	1

Notes: 1) Data are for both furnaces of the M/T Vulcanus.

2) Data on the concentration ranges of inorganics in the wastes and in stack emissions were collected and converted to mass emission rates. These rates were summed for all inorganics, and are considered to represent estimates of expected particulate emissions for the at-sea incineration of CMW wastes.

3) When two elements are listed, the noted emission rates are for each constituent.

TABLE 18. SUMMARY OF MAJOR AIR AND WATER QUALITY EFFECTS ASSOCIATION WITH AT-SEA INCINERATION

Air Quality ($\mu g/m^3$)(a)				Water Quality (ppb)		
HCl	Inorganics(b)	Unburned Wastes(c)	Copper(d)	HCl	Unburned Wastes	Copper
4422	22.49	2.75	0.22	197	0.09	.04

(a) Maxima for stipulated meteorological conditions: effective stack height = 125.5 meters, wind speed = 4.0 meters/second, surface reflectivity = 1.0 and stability category = D.

(b) Based on summation of inorganic constituents in wastes; provides an estimate of particulate concentrations.

(c) Based on lowest observed destruction efficiency (99.96%).

(d) Copper is the metallic waste constituent with the highest emission rate. Zinc's emission rate was equivalent to that of copper.

which give predicted concentrations at various distances downwind from the source are presented in Appendix B.

The HCl concentrations in the plume are expected to be high because there is no scrubbing of the combustion gases. Due to its buffering capacity, one cubic meter of ocean water is capable of neutralizing 80 gm of HCl (80,000 ppb) (Reference 17). Thus, a 197 ppb contribution of HCl from plume touchdown would never be detected by a pH change.

During a 1974 burn of CMW waste onboard the M/T Vulcanus, water samples were obtained in the vicinity of plume touchdown (Reference 16). Analysis of these samples showed no significant difference in pH and copper (the most abundant heavy metal constituent of the waste) as compared with samples from control areas. Organochlorine wastes were undetected at the 0.5 ppb level.

A Threshold Limit Value (TLV) of 7 mg/m^3 has been established for HCl. This level represents the maximum allowable HCl concentration for humans in a work area. Excursions beyond this level for periods greater than 15 minutes result in either intolerable irritation, or chronic or irreversible tissue damage (Reference 11). The maximum sea level HCl concentration of 4.4 mg/m^3 predicted as a result of at-sea incineration is below this TLV. It is also noticed that sea level plume impact is for short durations and at different points in the water.

The predicted maximum ambient unburned waste concentration is an order of magnitude larger than the corresponding ground level parameters for the land-based facility. More detailed information is required to determine the extent to which this emission is combined with particulate matter that may be a component of the combustion gases, or whether it is in the gaseous state. If associated with gravity settleable particulates, the impact of the unburned waste will be felt mostly in the water environments. If the emission is gaseous and the plume stays aloft for extended periods, then the impact of the unburned wastes will be felt in downwind areas. Information on the size distribution of the particulate matter emitted is required to answer questions about whether this material will be removed directly by gravity, or whether it will remain suspended and possibly serve as condensation nuclei. Under the latter set of conditions particulate matter (which could contain unburned wastes and heavy metals) could have adverse effects whenever washout does occur.

Biological specimens (phytoplankton and zooplankton) were also taken during the 1974 burn (Reference 16). Examination of chlorophyll-a (an indicator of phytoplankton activity) levels, and adenosine triphosphate (ATP) levels in the specimen showed no deleterious or subtle adverse impacts.

A series of biological tests were also associated with the March 1977 burn. Laboratory experiments with various concentrations of CMW waste culminated with the following results (Reference 19):

- Seven of 14 fish (fundulus Grandis) exposed to 74 ppm of CMW waste died within 41 hours. Death was apparently due to respiratory complications.
- At a concentration of 7.4 ppm, no effect on fish mortality was noted.
- Enzyme systems (catalase and P-450) of fish exposed to 1.0 ppm showed a marked response.

The P-450 enzymes are located in the liver and are required for the metabolism of foreign chemicals introduced into an organism. The response noted (an increase in the P-450 activity) reflects the presence of a foreign material that has to be metabolically altered prior to excretion. This effect is seen as an indication of a potential problem.

In addition to the laboratory tests, the same fish species was exposed to the plume of the M/T Vulcanus during incineration. Exposure was accomplished by using a device called a biotal ocean monitor (BOM), which allows specific organisms to be exposed under field conditions and then retrieved. The BOM tests showed an elevation in the activity of P-450 enzymes. However, when exposed fish were left in clean water for a few days, the enzyme activity reverted to those of control organisms.

It was concluded that the overall effects were localized and temporary, and do not represent drawbacks to the use of at-sea incineration for organochlorine waste disposal (Reference 19).

Metals are present in liquid organochlorine wastes; they will appear in the stack gases (and thus the plume) as particulate matter. The quantity of metal salts or metal oxides in the plume is independent of combustion efficiency and is directly proportional to the metal content of the waste itself. Control of the metal content of the waste, which is accepted for at-sea incineration where the effluent gases are not scrubbed, becomes the responsibility of regulatory agencies to ensure that wastes with unacceptably high metal content are not approved for burning at sea. Control must be implemented by restrictions based on the air and water quality requirements. Metal content permitted in waste thus becomes a function of the plume model and of the at-sea incineration, e.g., dilution in the plume, feed rate of waste, total combustion air and the speed of the incineration ship.

Malfunction Potential

A listing of some possible operational malfunctions during an at-sea incineration operation is shown in Table 19. The greatest possibility of spills is during loading. Hatches are open, samples are being taken, and exposed flex lines are under pressure. An additional source of contamination is the bilgewater from the pump room. Historically this material contains some of the pumped cargo. Bilges must not be pumped into channels, at dockside or at sea. This would be a procedural violation. Provision must be made to dispose of the bilge, possibly through the incinerator, where it can be burned with fuel.

If flameout occurs as the result of a slug of non-combustable material (e.g., water) entering the waste feed lines and passing through one or more burners, subsequent incoming waste will be vaporized. Vaporization will occur due to the latent heat in the incineration. This vapor will be emitted directly to the atmosphere. To prevent this failure mode, a positive and

TABLE 19. POTENTIAL OPERATIONAL MALFUNCTIONS DURING AN AT-SEA INCINERATION OPERATION

Operation	Possible Malfunction	Consequence
Tank Filling	1. Overfill on level interlock failure	Waste spill
	2. Leakage due to pump seal, valve packing material corrosion, etc.	Small waste spill
	3. Inclusion of unauthorized waste by subversion of quality control procedures	Possible incineration difficulties
Waste Transfer through Pump and Filter	1. Leakage due to pump seal, material corrosion, etc.	Small waste spill
	2. Deliberate bypassing of incinerator (ocean operations)	Waste spill
	3. Filter plugging	None if filters switched on high pump discharge pressure measurement
Waste Injection to Incinerator	1. Nozzle plugging (low flow detection)	Temporary shut-down
	2. Atomization air loss on air blower failure	Failure to combust, toxic vapor discharge, liquid accumulation
Incineration	1. Burner flame loss (flame-out) due to fuel loss of pressure, loss of primary combustion, air, coking, or water slug in feed	Transient toxic vapor discharge prior to automatic shutdown on flame loss detection (or lower combustion temperature. A water layer in the tank can be isolated by conductivity measurement interlock to the waste feed pump)
	2. Improper fuel rate	Excess waste product in discharge
	3. Improper air/fuel ratio	Inefficient combustion
	4. Injection into a cool combustion zone on start-up	Inefficient combustion

rapid waste feed shutoff system must be available. Such a system or device should rely on direct sensing of the burner flames (ultra-violet or infrared detectors) rather than secondary measurements which may have an inherent lag before response to a flameout.

4. CHLOROLYSIS

4.1 GENERAL DESCRIPTION

Chlorolysis, or chlorinolysis, is a process for converting organochlorine wastes to perchloroethylene, trichloroethylene and carbon tetrachloride as useful products. In the chlorolysis process, excess chlorine is added at temperatures in the 400° to 600°C range, so that the carbon-carbon bonds of hydrocarbons can be broken and the molecular fragments can react with chlorine to form chlorinated hydrocarbons of shorter chain length (Reference 20). Typical reactions in the chlorolysis process are:

$$C_2H_3Cl_3 + 4Cl_2 \rightarrow 2CCl_4 + 3HCl$$

$$C_4H_6Cl_2 + 10Cl_2 \rightarrow 4CCl_4 + 6HCl$$

$$C_4Cl_6 + 5Cl_2 \rightarrow 4CCl_4$$

According to Shiver (Reference 21), the U.S. patent literature indicates that Dow Chemical, Diamond Shamrock, and Pittsburgh Plate Glass have developed chlorolysis processes suitable for the conversion of C_1 through C_3 hydrocarbons to chlorinated solvents. In addition, Farberwerke Hoechst AG, the German affiliate of Hoechst-Uhde Corporation of New Jersey, has patented a chlorolysis process to manufacture carbon tetrachloride from organochlorine wastes.

The operating characteristics of the four chlorolysis processes are summarized in Table 20. Of these four chlorolysis processes, the Hoechst-Uhde process is the only one that has some capability of handling aromatic hydrocarbon feedstocks. This is because when chlorolyzing benzene and alkyl benzenes, hexachlorobenzene is formed as an intermediate which is reacted only above 500°C (Reference 20), and the lower reactor operating temperatures of the Diamond Alkali and Pittsburgh Plate Glass chlorolysis processes do not appear

TABLE 20. OPERATING CHARACTERISTICS OF CHLOROLYSIS PROCESSES*

Process Developer	Feedstock	Operating Conditions	Product Yield	Comments
Dow Chemical	C_1, C_2, C_3 hydrocarbon products & their partially chlorinated derivatives.	600°C	94-95% of perchloroethylene and carbon tetrachloride, 6% of hexachlorobenzene.	Hexachlorobenzene is one of the hard to treat wastes.
Diamond Alkali	Ethylene dichloride.	400°C, using Fuller's earth as catalyst in fluid bed	90% yield of perchloroethylene and trichloroethylene; the balance estimated to be hexachloroethane, hexachlorobutadiene, hexachlorobenzene, tetrachloroethane, pentachloroethane.	The tetrachloroethane & pentachloroethane can be recycled and pyrolized to trichloroethylene. The hexachlorobutadiene & hexachlorobenzene are expected to be residues from this process.
Pittsburgh Plate Glass	Ethylene dichloride and other C_2 chlorohydrocarbons.	400°C, oxychlorination in a fluid bed catalytic reactor	85% yield of trichloroethylene and perchloroethylene; the balance probably carbon oxides, and chlorohydrocarbons such as hexachlorobutadiene and hexachlorobenzene.	Relatively low yield to useful products. The hexachlorobutadiene and hexachlorobenzene formed are expected to be residues from this process.
Hoechst Uhde	C_1 to C_6 organochlorine compounds.	600°C and 20 MPa	>95% yield of carbon tetrachloride per pass. Heavy ends consist chiefly of hexachlorobenzene.	Very high overall yield to carbon tetrachloride if the presence of oxygenated chlorohydrocarbons in the feedstocks is limited. The hexachlorobenzene formed can be recycled to extinction.

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* The information source for the Dow Chemical, Diamond Alkali and Pittsburgh Plate Glass processes is Reference 21. Information on the Hoechst-Uhde process was obtained from Reference 3.

to be adequate to convert the hexachlorobenzene to useful products. Also, with the exception of chlorinated alkanes, chlorolysis of chlorinated hydrocarbons is favored at higher reactor pressures. Chlorolysis of chlorinated aromatic hydrocarbons in the Hoechst-Uhde reactor, at 20 MPa, is therefore more thermodynamically favorable. For the same reasons, the Hoechst-Uhde process is the only chlorolysis process that does not produce organochlorine residues in sizable quantities, as all wastes initially produced can be recycled to extinction.

The Hoechst-Uhde process is the chlorolysis process considered in the present study. A demonstration plant producing 8,000 metric tons per year of carbon tetrachloride has been in operation in Frankfurt, Germany since November 1970. More recently, a commercial plant producing 50,000 metric tons per year of carbon tetrachloride has been on stream at the same site since 1977, and two chlorolysis plants have been sold to the Soviet Union. A detailed description of the Hoechst-Uhde chlorolysis process is provided in Section 4.3.

Theoretically, most organochlorine wastes could be used as feedstocks for the Hoechst-Uhde chlorolysis process. Suitable feedstocks include those residues from the production of vinyl chloride monomer, chloromethanes, propylene oxide, allyl chloride, perchloroethylene, as well as residues from benzene chlorination. The presence of other elements besides carbon, hydrogen, and chlorine, however, could lead to problems in regard to product handling and corrosion. Particulate matter, for example, poses a significant mechanical problem in the operation and maintenance of control equipment. The presence of small amounts of sulfur is extremely corrosive to any nickel-containing material. With this in mind, the sulfur content of the feedstock must be kept below 25 ppm. This is achievable in practice by dilution of the sulfur feedstock with other feedstock which can be processed in a given amount of time.

The effects of nitrogen and/or phosphorus in combination in the feedstock are unknown at this time. To guard against the possible formation of nitrogen trichloride (NCl_3) and phosphorus trichloride (PCl_3), chlorolysis feedstocks are analysed to assure that no nitrogen and/or phosphorus are present. Neither compound is desirable as nitrogen trichloride is explosive and phosphorus trichloride is pyrophoric. The emissions which might be generated include NO_2, and P_2O_5 dependent upon combustion conditions.

In summary, acceptable feedstocks for chlorolysis should be free of particulates. The sulfur content should not exceed 25 ppm. The feed stream should not contain nitrogen or phosphorus. To limit the reaction temperature to the maximum reactor design temperature of 620°C, an additional restriction of a maximum of 5 percent aromatic hydrocarbons, calculated as benzene, was placed on the Hoechst-Uhde design. In an industry survey, Shiver has shown that available organochlorine wastes suitable as chlorolysis feedstocks include 23,000 to 27,000 metric tons per year of vinyl chloride monomer residue and 19,500 metric tons per year of chlorinated solvent waste (Reference 21). Geographically, these wastes are generated primarily at Gulf Coast locations from Corpus Christi, Texas to New Orleans, Louisiana (Reference 3). The concentration of these wastes along the Gulf Coast indicates that a Houston, Texas location would be suitable for the cost analysis and environmental assessment of the Hoechst-Uhde chlorolysis process.

4.2 COST ANALYSIS

The cost analysis performed was based on estimates provided in the Hoechst-Uhde report (Reference 3). The two wastes for which cost data are available include a mixed vinyl chloride monomer (VCM) and chlorinated solvent waste and a vinyl chloride monomer (VCM) waste. The first waste, considered by Hoechst-Uhde as the base case, contains 60 percent by weight of VCM residues, and 40 percent by weight of chlorinated solvent wastes. According to the experience of Hoechst AG with various organochlorine wastes, 40 percent is the maximum quantity of solvent wastes which can be mixed with VCM residues. The reason for the limitation is material problems caused by the requirement that feed chlorine would have to be heated up to a temperature in excess of 250°C. The second waste, produced during the manufacture of vinyl chloride monomer, consists of 33 percent by weight of light ends and 67 percent by weight of heavy ends distillate. Selected properties of these two organochlorine wastes have been previously given in Table 3.

The discussion on cost analysis is divided into capital investment cost, annual operating costs, and unit disposal costs.

4.2.1 Capital Investment

The capital investment cost for a chlorolysis plant processing 25,000 metric tons per year of organochlorine waste, as estimated in the Hoechst-Uhde study, was $25,496,900 for the first half of 1977 (Reference 3). Adjusted to March 1978 basis using the Chemical Engineering Plant Cost Index, the total capital investment cost was estimated to be $27,210,000.

The capital investment cost estimated by Hoechst-Uhde was based on a new plant location with a clear and level site in the Gulf Coast area. It was also assumed that foundations can be installed with conventional spread footings and that a pumping station would not be required to provide cooling water to the plant. Land costs and all startup costs were also excluded.

4.2.2 Annual Operating Costs

The annual operating costs for the chlorolysis of organochlorine wastes consist of the costs of chemicals, utilities, operating labor, maintenance, overhead expenses, taxes and insurance, and process royalty. The raw material and operating requirements for the chlorolysis of the mixed VCM and solvent waste and the VCM waste were obtained directly from the Hoechst-Uhde study (Reference 3). The net annual operating costs for the mixed VCM and solvent waste and the VCM waste, as presented in Tables 21 and 22, are $16,011,800 and $19,881,800, respectively.

The difference in the net annual operating costs for the chlorolysis of the two organochlorine wastes is due to the difference in the process chlorine requirement. For the mixed VCM and solvent waste, 68,000 metric tons per year of chlorine are needed to convert 25,000 metric tons per year of waste to 75,000 metric tons per year of carbon tetrachloride and 17,850 metric tons per year of hydrogen chloride. For the VCM waste, 93,800 metric tons per year of chlorine are needed to convert 25,000 metric tons per year of waste

TABLE 21. ANNUAL OPERATING COST FOR PROCESSING 25,000 METRIC TONS/YEAR OF A MIXED VINYL CHLORIDE MONOMER AND SOLVENT WASTE AT A CHLOROLYSIS PLANT

Item	Cost, $/Year
Chemicals	
Chlorine: 68,000 metric tons @ $150/metric ton	$ 10,200,000
20% Caustic: 14,500 metric tons @ $30/metric ton	435,000
Methane: 134,500,000 ft^3 @ $2/1000 ft^3	269,000
Utilities	
Electric power: 25,600,000 Kw-hr @ $0.015/Kw-hr	384,000
Steam: 52,000 metric tons @ $4/metric ton	208,000
Cooling water: 3.9 x 10^9 gallons @ $0.01/1000 gallons	39,000
Operating Labor	
Operator, 10 men/shift, $8.65/manhour	755,700
Direct supervision, 4 men, $12.12/manhour	100,800
Maintenance	
Maintenance labor, 2% of Total Plant Cost	544,200
Maintenance supply, 2% of Total Plant Cost	544,200
Direct Overhead	
(30% of Operating Labor and Supervision)	257,000
General Plant Overhead	
(50% of Operating and Maintenance Labor and 3% of Total Plant Cost)	1,516,700
Taxes and Insurance	
(1.5% of Total Plant Cost)	408,200
Royalty	350,000
Net Annual Operating Cost	$ 16,011,800

TABLE 22. ANNUAL OPERATING COST FOR PROCESSING 25,000 METRIC TONS/YEAR OF VINYL CHLORIDE MONOMER WASTE AT A CHLOROLYSIS PLANT

Item	Cost, $/Year
Chemicals	
Chlorine: 93,800 metric tons @ $150/metric ton	$ 14,070,000
20% Caustic: 14,500 metric tons @ $30/metric ton	435,000
Methane: 134,500,000 ft^3 @ $2/1000 ft^3	269,000
Utilities	
Electric power: 25,600,000 Kw-hr @ $0.015/Kw-hr	384,000
Steam: 52,000 metric tons @ $4/metric ton	208,000
Cooling water: 3.9 x 10^9 gallons @ $0.01/1000 gallons	39,000
Operating Labor	
Operator, 10 men/shift, $8.65/manhour	755,700
Direct supervision, 4 men, $12.12/manhour	100,800
Maintenance	
Maintenance labor, 2% of Total Plant Cost	544,200
Maintenance supply, 2% of Total Plant Cost	544,200
Direct Overhead	
(30% of Operating Labor and Supervision)	257,000
General Plant Overhead	
(50% of Operating and Maintenance Labor and 3% of Total Plant Cost)	1,516,700
Taxes and Insurance	
(1.5% of Total Plant Cost)	408.200
Royalty	350,000
Net Annual Operating Cost	$ 19,881,800

to 88,500 metric tons per year of carbon tetrachloride and 30,000 metric tons per year of hydrogen chloride.

At a carbon tetrachloride selling price of $300 per metric ton, and a hydrogen chloride selling price of $50 per metric ton, the annual revenue derived from the sale of these two products would be $23,392,500 from the chlorolysis of the mixed VCM and solvent waste, and $28,050,000 from the chlorolysis of the VCM waste. Thus, the cost associated with the higher process chlorine requirement could be more than offset by higher product credits.

4.2.3 Unit Disposal Cost

As discussed in the cost analysis for land-based incineration, the method used for estimating the unit disposal cost of organochlorine wastes is based on the discounted cash flow technique. Calculation of discounted cash flow for the chlorolysis of the mixed VCM and solvent waste is illustrated in Table 23. The calculation procedure follows that described by Uhl (Reference 7), and the assumptions used are discussed in detail in Appendix A. It showed that at 15% DCFRR, an annual cash flow of $7,023,300 must be generated to offset the expenditures in capital investment, working capital and startup cost. With a net annual operating cost of $16,011,800, and assuming 10 year straight line depreciation and an income tax rate of 50%, the annual revenue that must be generated was calculated to be $27,337,400. As the annual revenue obtained from the sale of carbon tetrachloride and hydrochloric acid was calculated to be $23,392,500, the additional revenue to be derived from waste disposal charges would be $3,944,900. Unit disposal cost is, therefore, $157.79 per metric ton.

The calculation of discounted cash flow for the chlorolysis of the VCM waste is shown in Table 24. At 15% DCFRR, the annual cash flow and the annual revenue that must be generated were calculated to be $7,114,500 and $31,389,800, respectively. For the VCM waste, the annual revenue obtained from the sale of carbon tetrachloride and hydrochloric acid was calculated to be

TABLE 23. CALCULATION OF DISCOUNTED CASH FLOW FOR CHLOROLYSIS OF MIXED VINYL CHLORIDE MONOMER AND SOLVENT WASTE AT 15% DISCOUNTED CASH FLOW RATE OF RETURN

Time, Year	Item	Investment	Cash Flow	Discounting Factor	Discounted Cash Flow
-2 to 0	Depreciable Investment	$ 27,210,000		1.1662	- $ 31,732,194
0	Working Capital	$ 4,100,607		1.0	- $ 4,100,607
1	Interest on 30% of Total Plant Cost at 10% Rate		- 0.5* ($ 1,823,614)	0.9048	- $ 825,037
0 to 2	Startup Cost		- 0.5* ($ 1,360,500)	0.9286	- $ 631,689
0 to 10	Cash Flow		10 ($ 7,023,290)	0.5179	$ 36,374,558
10	Recover Working Capital	- $ 4,100,607		0.2231	$ 914,969
					0

* The actual cash flow for these two items are reduced by 50% due to the effect on cash flow of income tax.

TABLE 24. CALCULATION OF DISCOUNTED CASH FLOW FOR CHLOROLYSIS OF VINYL CHLORIDE MONOMER WASTE AT 15% DISCOUNTED CASH FLOW RATE OF RETURN

Time, Year	Item	Investment	Cash Flow	Discounting Factor	Discounted Cash Flow
-2 to 0	Depreciable Investment	$ 27,210,000		1.1662	- $ 31,732,194
0	Working Capital	$ 4,708,303		1.0	- $ 4,708,303
1	Interest on 30% of Total Plant Cost at 10% Rate		- 0.5* ($ 1,823,614)	0.9048	- $ 825,037
0 to 2	Startup Cost		- 0.5* ($ 1,360,500)	0.9286	- $ 631,689
0 to 10	Cash Flow		10 ($ 7,114,446)	0.5179	$ 36,846,659
10	Recover Working Capital	- $ 4,708,303		0.2231	$ 1,050,564
					0

* The actual cash flow for these two items are reduced by 50% due to the effect on cash flow of income tax.

$28,050,000. Thus, the additional revenue to be derived from waste disposal charges would be $3,339,800. The unit disposal cost for the VCM waste is, therefore, $133.59 per metric ton.

Unit disposal costs for organochlorine wastes can also be more readily calculated using the unit disposal cost equation described in Appendix A. In Table 25, the different cost elements that contribute to the unit disposal costs for the mixed VCM and solvent waste and the VCM waste at a chlorolysis plant are presented. It is seen that the unit disposal cost is very dependent on the carbon tetrachloride sales credit.

The CMW waste, the perchloroethylene waste, and the hexachlorocyclopentadiene waste considered in the cost analysis of land-based and at-sea incineration are not, strictly speaking, suitable feedstocks for the chlorolysis process. The sulfur contents for the CMW waste and the hexachlorocyclopentadiene waste are 90 ppm and 200 ppm, respectively, both exceeding the 25 ppm sulfur limit. The perchloroethylene waste contains 9.2 percent by weight of chlorinated benzene, exceeding the 5 percent by weight limit for aromatics. However, all three wastes can be blended with VCM wastes to meet the chlorolysis feedstock acceptability criteria. For comparison purposes, the unit disposal costs for these three organochlorine wastes at 15% DCFRR were estimated to be $196 per metric ton for the CMW waste, $136 per metric ton for the perchloroethylene waste, and $196 per metric ton for the hexachlorocyclopentadiene waste. For the CMW waste and the hexachlorocyclopentadiene waste, the presence of oxygen leads to formation of carbonyl chloride and a lower yield of carbon tetrachloride. The carbonyl chloride obtained is assumed to be sent to the incineration unit for disposal and not recovered as a product. The higher unit disposal cost for these two wastes is the direct result of the lower carbon tetrachloride yield.

The pronounced effect of carbon tetrachloride selling price on the unit disposal costs for the mixed VCM and solvent waste and the VCM waste is illustrated in Figure 2. At 15% DCFRR, it is seen that the unit disposal cost would increase to $248 per metric ton for the mixed VCM and solvent waste

TABLE 25. UNIT DISPOSAL COST FOR ORGANOCHLORINE WASTES AT A CHLOROLYSIS PLANT

Item	$/Metric Ton Waste	
	VCM and Solvent Waste	VCM Waste
Operating Cost		
Chlorine	408.00	562.80
Caustic	17.40	17.40
Methane	10.76	10.76
Electric power	15.36	15.36
Steam	8.32	8.32
Cooling Water	1.56	1.56
Operating Labor	34.26	34.26
Maintenance	43.53	43.53
Overhead expense	70.95	70.95
Taxes and Insurance	16.33	16.33
Royalty	14.00	14.00
Subtotal	640.47	795.27
Capital Investment Related Items	394.06	394.06
Working Capital	49.21	56.50
Startup Cost	9.76	9.76
Sales of Carbon Tetrachloride	- 900.00	- 1,062.00
Sales of Hydrochloric Acid	- 35.71	- 60.00
Unit Disposal Cost	157.79	133.59

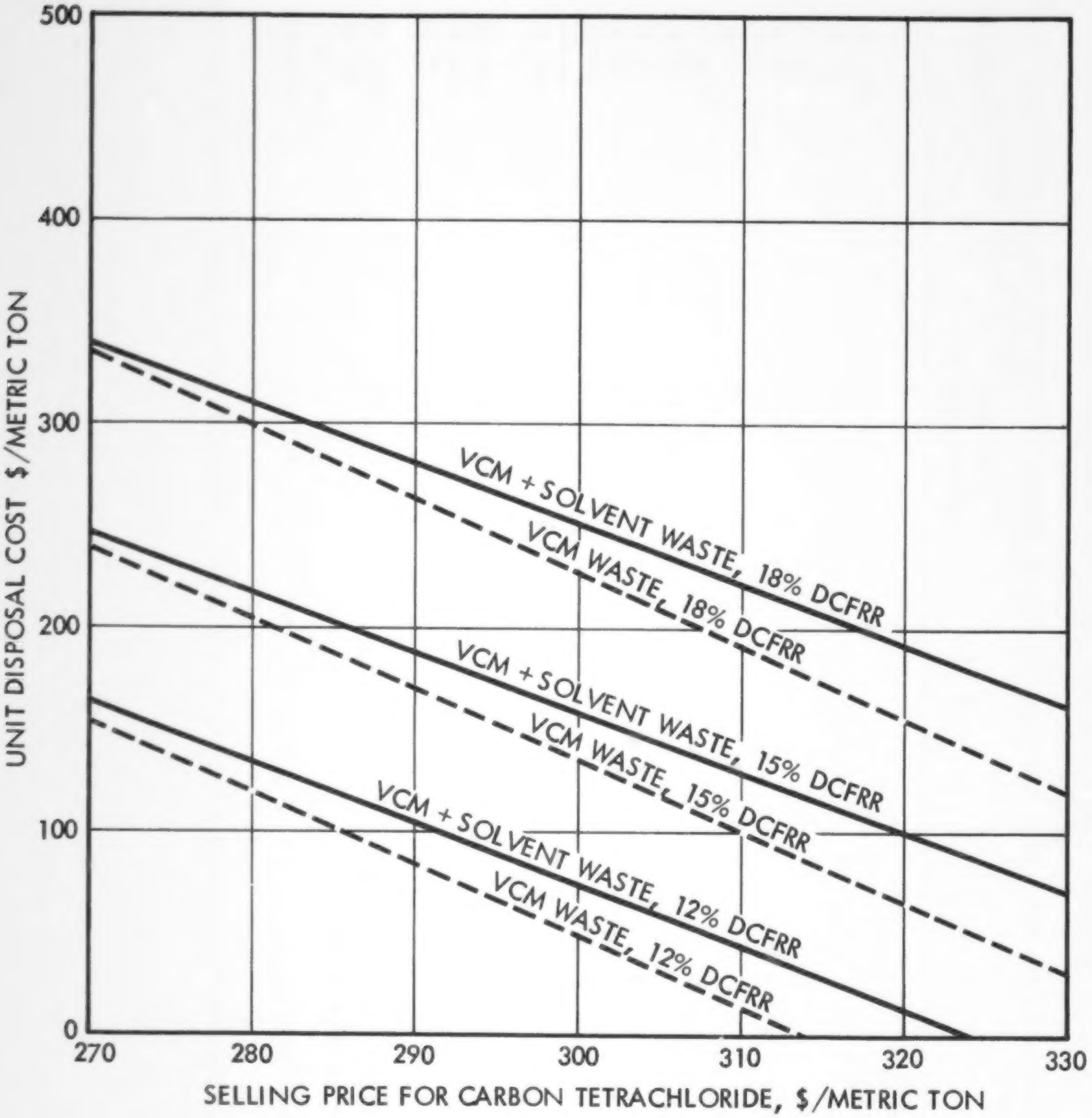

Figure 2. Effect of carbon tetrachloride selling price and discounted cash flow rate of return (DCFRR) on unit disposal cost of organochlorine wastes by chlorolysis.

and $240 per metric ton for the VCM waste, if the selling price for carbon tetrachloride falls to $270 per metric ton. On the other hand, the unit disposal cost would decrease to $68 per metric ton for the VCM and solvent waste and $27 per metric ton for the VCM waste, if the selling price for carbon tetrachloride rises to $330 per metric ton. Thus, the unit disposal cost for organochlorine wastes by chlorolysis is extremely sensitive to the selling price for carbon tetrachloride.

The effect of discounted cash flow rate of return on the unit disposal cost of organochlorine wastes by chlorolysis is also illustrated in Figure 2. At 12% DCFRR, the unit disposal cost would be approximately $84 per metric ton lower than at 15% DCFRR. At 18% DCFRR, the unit disposal cost would be approximately $93 per metric ton higher than at 15% DCFRR.

The results of cost analysis have indicated that the economic viability of the chlorolysis process is totally dependent on the selling price for carbon tetrachloride. As discussed in the Hoechst-Uhde report (Reference 3), the total volume of carbon tetrachloride produced is estimated to be about 400,000 metric tons per year. About 80% of the carbon tetrachloride produced is used in the manufacture of Freon-11 and 12 for refrigeration and propellant usage. The use of fluorocarbon aerosol propellants, however, has already been reduced by 50% due to the current concern about the depletion of the ozone layer attributed to the C_1 fluorocarbons. In the Hoechst-Uhde analysis, the production level for carbon tetrachloride is expected to be stabilized at about 310,000 metric tons per year, partly by adjustments in the product mix of plants that coproduce carbon tetrachloride with either perchloroethylene or methylene chloride and chloroform. For a chlorolysis plant processing 25,000 metric tons of organochlorine wastes per year, the volume of carbon tetrachloride produced would be 75,000 to 100,000 metric tons per year, depending on the carbon content of the feedstock. This volume of carbon tetrachloride represents 24 to 33% of the projected stabilized market, a level which cannot be readily absorbed without causing major pertubations in the pricing structure.

4.3 ENVIRONMENTAL ASSESSMENT

4.3.1 Emissions Characterization for Chlorolysis

The chlorolysis plant, as designed by Hoechst-Uhde Corp., consists of a pretreatment section for the treatment of all wastes entering the unit; a reactor section where the treated residues are converted into hydrogen chloride (HCl) and carbon tetrachloride (CCl_4), a distillation section for the separation of reaction products, and an incineration section for the disposal of remaining residues. An absorption unit is used for the elimination of all waste gases containing chlorine gas (Cl_2) and HCl for normal and emergency shut-down situations. A simplified flow diagram is shown in Figure 3.

The wastes used in this process are characterized by their production processes. The vinyl chloride wastes are unique in that they contain hydrogen whereas the solvent wastes do not. This occurs because of the higher degree of chlorination and higher temperature required to make chlorinated solvents. Typical analyses of the waste fractions are shown in Table 26.

The components in these wastes range from C_1 through C_6 organochlorine compounds. They are all suitable feeds for the chlorolysis process. A normal feed rate for a chlorolysis unit is a mixture of 60 percent by weight vinyl chloride waste and 40 percent by weight solvent wastes. The description is based upon a 25,000 metric tons per year process. Emission estimates for the chlorolysis process were obtained from the Hoechst-Uhde report (Reference 3).

Pretreatment Section (See Figure 4)

The pretreatment for light ends consists of adsorbers with a regeneration system. The wet light ends are passed through the adsorption unit with the dried organics flowing into a holding tank. The regeneration system, consisting of a scrubber and a separator, renews one adsorber while the other is being charged. Any residue from the separator is sent to the incineration unit for disposal. The distillate is sent to a holding tank.

In the pretreatment for heavy ends, the waste residues are separated from the tarry residues and soot. The system contains evaporators, a separator,

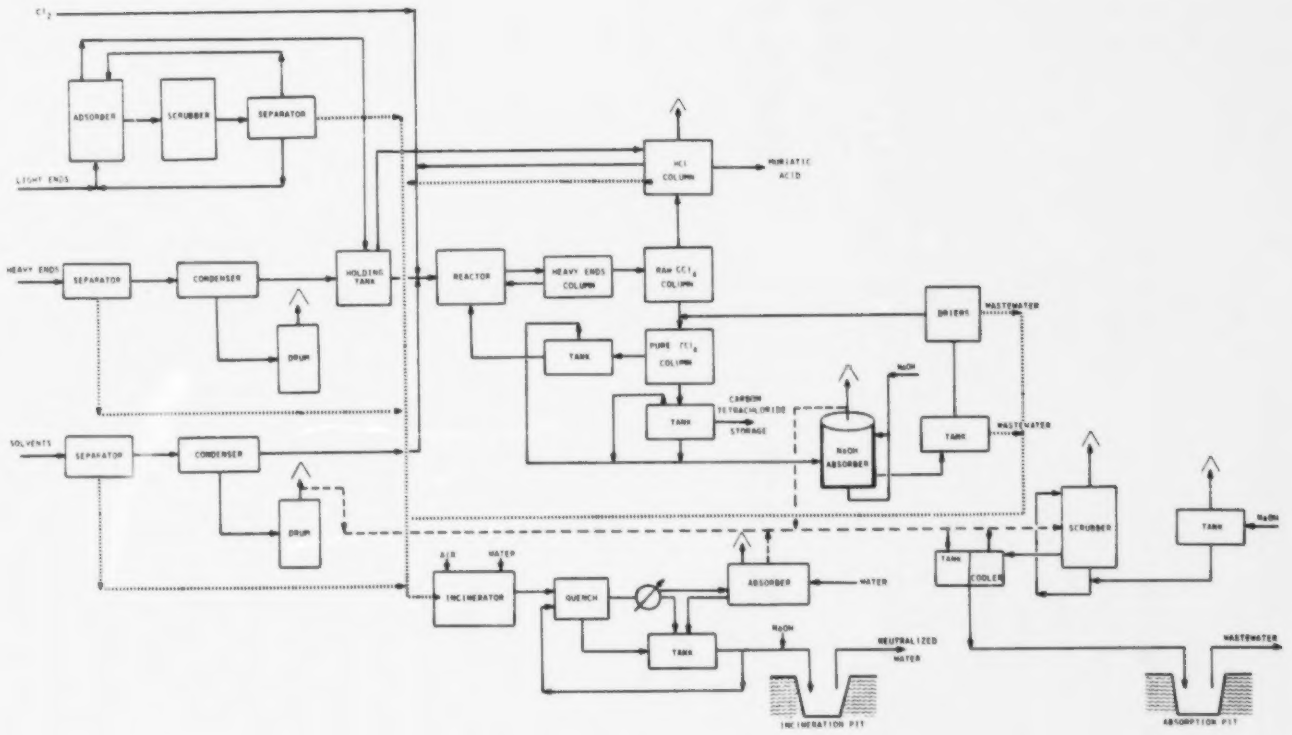
Cl_2
LIGHT ENDS
ADSORBER
SCRUBBER
SEPARATOR
HEAVY ENDS
SEPARATOR
CONDENSER
DRUM
HOLDING TANK
SOLVENTS
SEPARATOR
CONDENSER
DRUM
REACTOR
HEAVY ENDS COLUMN
RAW CCl_4 COLUMN
HCl COLUMN
MURIATIC ACID
TANK
PURE CCl_4 COLUMN
TANK
CARBON TETRACHLORIDE STORAGE
NaOH ABSORBER
NaOH
DRIERS
WASTEWATER
TANK
WASTEWATER
AIR
WATER
INCINERATOR
QUENCH
ABSORBER
WATER
TANK
NaOH
NEUTRALIZED WATER
INCINERATION PIT
TANK
COOLER
SCRUBBER
TANK
NaOH
WASTEWATER
ABSORPTION PIT

Figure 3. Flow diagram for the Hoechst-Uhde chlorolysis process. (Emission sources are indicated by $\widehat{\uparrow}$)

TABLE 26. ANALYSES OF VINYL CHLORIDE MONOMER AND CHLORINATED SOLVENTS WASTE FRACTIONS

Light Ends (Vinyl Chloride Monomer)		Percent by Weight
Chloroethylene	C_2H_3Cl	10.9
Chloroethane	C_2H_5Cl	3.8
Dichloroethylene	$C_2H_2Cl_2$	4.5
Trichloromethane	$CHCl_3$	9.9
Chlorobutadiene	C_4H_5Cl	14.5
Dichloroethane	$C_2H_4Cl_2$	30.4
Carbon Tetrachloride	CCl_4	16.9
Benzene	C_6H_6	6.2
Trichloroethylene	C_2HCl_3	2.9
TOTAL		100.0
Heavy Ends (Vinyl Chloride Monomer)		**Percent by Weight**
Dichloroethylene	$C_2H_2Cl_2$	0.5
Chlorobutadiene	C_4H_5Cl	2.7
Dichloroethane	$C_2H_4Cl_2$	2.2
Carbon Tetrachloride	CCl_4	0.7
Dichloropropane	$C_3H_6Cl_2$	1.7
Trichloroethane	$C_2H_3Cl_3$	56.6
Dichloropropene	$C_3H_4Cl_2$	2.7
Dichlorobutene	$C_4H_6Cl_2$	26.0
Trichloropropene	$C_4H_6Cl_3$	6.7
Chlorobenzene	C_6H_5Cl	2.8
Tetrachloroethane	$C_2H_2Cl_4$	2.3
Dichlorobenzene	$C_6H_4Cl_2$	1.1
TOTAL		100.0
Solvents		**Percent by Weight**
Hexachloroethane	C_2Cl_6	25.0
Hexachlorobutadiene	C_4Cl_6	65.0
Hexachlorobenzene	C_6Cl_6	10.0
TOTAL		100.0

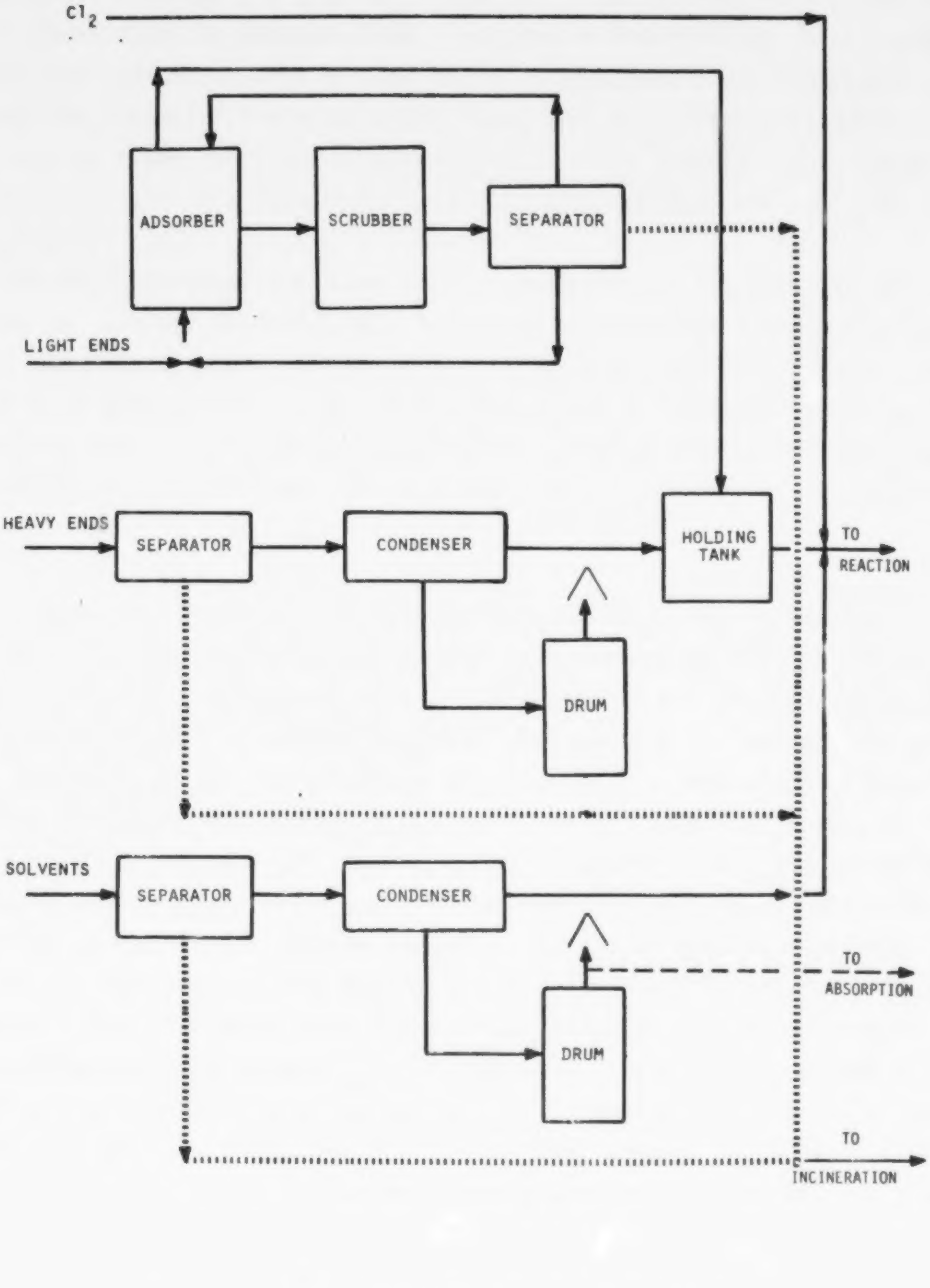
Cl_2
ADSORBER
SCRUBBER
SEPARATOR
LIGHT ENDS
HEAVY ENDS
SEPARATOR
CONDENSER
HOLDING TANK
TO REACTION
DRUM
SOLVENTS
SEPARATOR
CONDENSER
TO ABSORPTION
DRUM
TO INCINERATION

Figure 4. Pretreatment section

condensers, collection drums and sealing drums. A distillation process operating under a vacuum is used to minimize the thermal load (this helps avoid polymerization and coking). Surface condensers are employed to minimize the production of contaminated wastewater. Small amounts of uncondensed organic components are transferred into the sealing drum where they are routed to the incineration unit. The drum vents approximately 6 kilograms per hour of air with traces of heavy ends. For corrosion protection, small amounts of ammonia (NH_3) are fed into the drum to obtain a slightly alkaline solution.

In the pretreatment for solvents, the residues are separated from the sooty solid materials and polymers by use of a distillation system. As above, there is a vent to the atmosphere which yields approximately 6 kilograms per hour of air with traces of solvents. From this system, the residue from the evaporator as well as the wastewater from the receiving drum is sent to the incineration unit. The distillate is transferred into the reactor holding drum.

Pretreatment of the waste material appears essential for effective operation of the chlorolysis process. Excess moisture, particulate matter, contamination products and certain elements must be removed or diluted before entering the reactor. Light ends may contain a maximum of 0.1 percent dissolved water. Heavy ends and solvents may contain soot, coking products, polymer or undesirable elements which are not converted quantitatively to carbon tetrachloride (CCl_4) and hydrogen chloride (HCl). The non-volatile organics and particulate matter tend to accumulate. These particulates pose a significant mechanical problem in the operation and maintenance of control equipment. They usually consist of fine carbon particles and catalyst fragments. The mere size of these particles makes conventional filtration difficult. Therefore, the evaporation method is more suitable for removal of these particles. The component hexachlorobenzene (C_6Cl_6) contained in the solvent residue is not totally soluble at ambient temperature. To maintain its solubility, the hold tank must be kept in a narrow temperature range.

Reaction Section (See Figure 5)

Chlorolysis is a recycling process. The by-product residues of the varied chlorination processes are recycled into the feed stream in order to convert them into carbon tetrachloride and hydrogen chloride. More than 99 percent of the chlorine in the feed streams is converted to carbon tetrachloride and hydrogen chloride. The by-products are recycled to extinction.

Chlorolysis reactions are all exothermic. Reactions take place at temperatures up to 600°C with pressures of 18.1 MPa absolute. The heat of reaction is sufficient for adiabatic reaction with the temperature controlled by the amount of chlorine produced. Temperatures must not exceed 620°C due to material limitations. Exact reaction conditions are dependent upon the residue composition. The following equations illustrate some characteristic oxidations:

$$\begin{array}{lcrcrcr}
CHCl_3 & + & Cl_2 & \rightarrow & CCl_4 & + & HCl \\
C_2H_4Cl_2 & + & 5\ Cl_2 & \rightarrow & 2\ CCl_4 & + & 4\ HCl \\
C_6H_6 & + & 15\ Cl_2 & \rightarrow & 6\ CCl_4 & + & 6\ HCl \\
C_6Cl_6 & + & 9\ Cl_2 & \rightarrow & 6\ CCl_4 & &
\end{array}$$

Hexachlorobenzene is formed as an intermediate product when benzene (C_6H_6) and alkylbenzenes are chlorolyzed. Hexachlorobenzene only reacts above 500°C.

Chlorine, the light ends distillate, the heavy ends distillate, the solvent distillate, and the recycled residues are fed into a reactor. The primary sections of the reactor are heated, initiating reactions and compensating for any heat losses. The final reactor section functions as a quench section. The reaction products are quenched from 600°C to 500°C by the injection of carbon tetrachloride (recycled from the "pure" CCl_4 column). The products are cooled further by a reduction in pressure, via a pressure relief valve, as a result of the Joule-Thomson effect, before entering the distillation section.

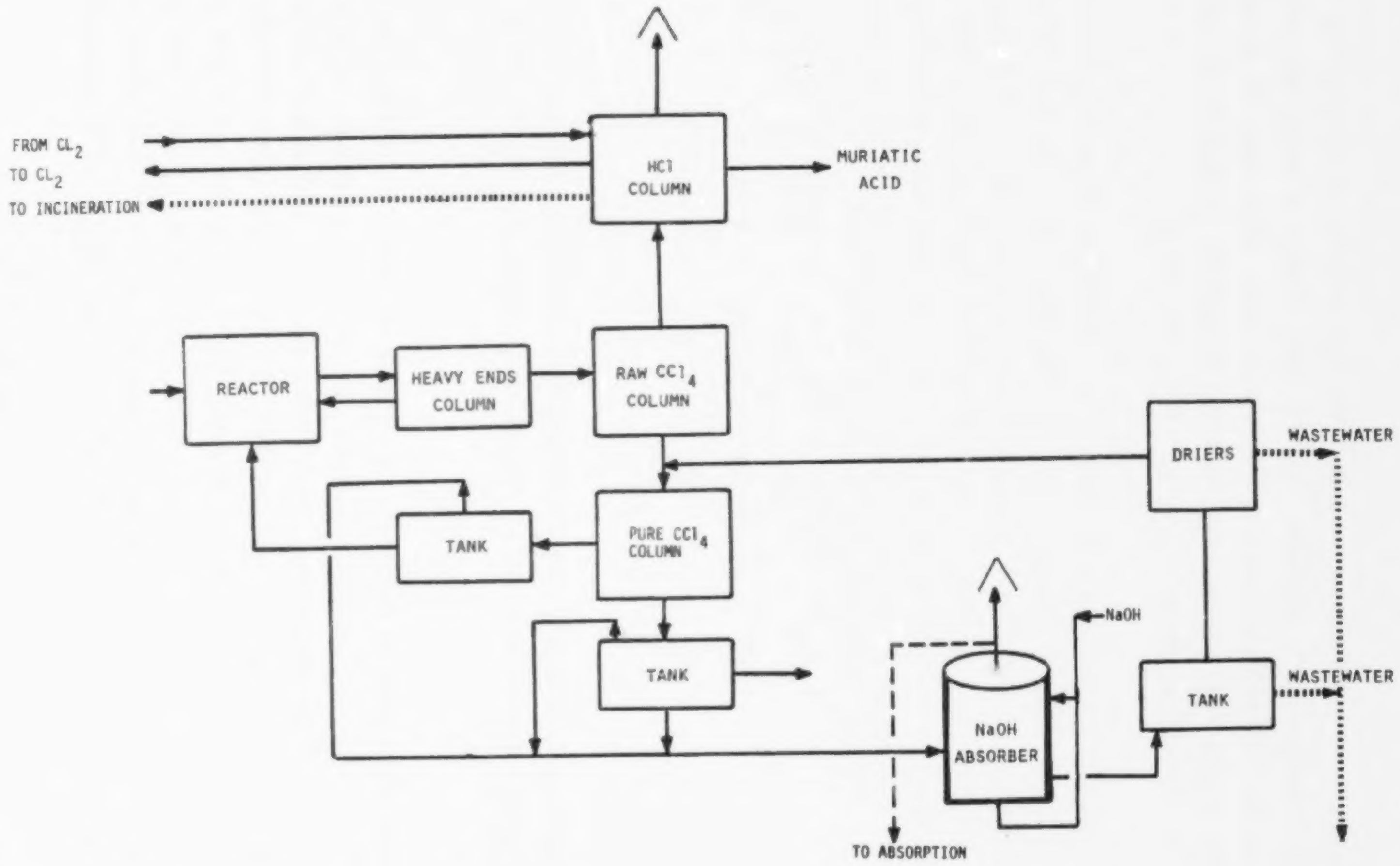
FROM CL_2
TO CL_2
TO INCINERATION
HCl COLUMN
MURIATIC ACID
REACTOR
HEAVY ENDS COLUMN
RAW CCl_4 COLUMN
DRIERS
WASTEWATER
TANK
PURE CCl_4 COLUMN
TANK
NaOH
NaOH ABSORBER
TANK
WASTEWATER
TO ABSORPTION

Figure 5. Reaction and distillation section.

Distillation Section (See Figure 5)

From the reactor, the product stream enters a heavy ends column to continue the reaction process. Unconverted hexachlorobenzene and hexachloroethane (C_2Cl_6) are separated and recycled back into the primary reactor. Other products recycled include carbonyl chloride ($COCl_2$) and iron chloride ($FeCl_3$). The formation of carbonyl chloride occurs when there are feedstock compounds containing oxygen. The iron chloride is surplus catalyst. Small amounts of soot also are recycled into the reactor. Carbon dioxide (CO_2) as well as carbonyl chloride are formed from the oxygen containing feedstock. Gaseous hydrogen chloride, Cl_2, CCl_4, and small amounts of $COCl_2$, and CO_2 are discharged as overhead product into a "raw" carbon tetrachloride column.

In the "raw" carbon tetrachloride column, the products undergo further separation. The bottom product consisting of carbon tetrachloride, carbonyl chloride, small amounts of bromine and traces of chlorine, hexachlorobenzene, and hexachloroethane enters a "pure" carbon tetrachloride column. Overhead products from the "raw" carbon tetrachloride column (HCl, CO_2, Cl_2, and $COCl_2$) are drawn off and sent to the HCl column. As overhead product, HCl is drawn off this column with small amounts of CO_2 and stored at the plant for further use. Compounds vented from this column are shown in Table 27. Chlorine, containing traces of carbonyl chloride and carbon tetrachloride is drawn off as a side stream from the HCl column. This stream along with fresh chlorine from storage is recycled into the reactor feed. The bottom product from the HCl column (a mixture of carbonyl chloride, carbon tetrachloride and chlorine) is

TABLE 27. EMISSIONS FROM THE HCl COLUMN CHLOROLYSIS PROCESS, BASED UPON 25,000 METRIC TONS/YEAR

Compound	Emission Rate
HCl	4.28 kg/hr
Cl_2	0.43 gm/hr
CCl_4	0.21 gm/hr
$COCl_2$	0.21 gm/hr

sent to the incineration unit. (If the carbonyl chloride were to be used in an isocyanate process, it would need to be rectified. As the quantity obtained is minimal, it is not economical to provide a column and a storage vessel with a filling device equipped with the safety facilities required for this hazardous substance.) The HCl column system is designed with a buffer volume surge capacity of approximately three hours of operation.

The bottom products from the "raw" CCl_4 column are sent to the "pure" CCl_4 column where they are distilled into pure carbon tetrachloride. A portion of the distilled carbon tetrachloride is pumped into a holding vessel, with the remainder sent to storage. The stored carbon tetrachloride is used as needed, for the quenching operation in the final reactor sections. Also recycled into the reactor from the CCl_4 column are small quantities of bromine, chlorine, carbonyl chloride, hexachlorobenzene and hexachloroethane. Small amounts of uncondensed components (usually CCl_4, Cl_2, HCl, $COCl_2$, Br) are fed into an absorber where purification is achieved by scrubbing with a 20 percent NaOH solution. The vented emissions from this absorber are shown in Table 28. The bottom product from the absorber is separated into wastewater and carbon tetrachloride streams. The wastewater stream, lighter than the carbon tetrachloride stream, flows to the incineration unit while the CCl_4 is passed through driers before re-entering the pure CCl_4 column. The wastewater stream will contain the various trace metals which were present in the feedstock. Most will remain as residue in the pit. Any bromine present as impurity in the feedstock will be discharged in the wastewater from the incineration pit as traces of sodium bromide (NaBr) and sodium hypobromite (NaOBr).

TABLE 28. EMISSIONS FROM THE NaOH ABSORBER CHLOROLYSIS PROCESS, BASED UPON 25,000 METRIC TONS/YEAR

Compound	Emission Rate, mg/hr
HCl	30.0
$COCl_2$	10.0
CCl_4	500.0

Incineration Section (See Figure 6)

All pretreatment chlorinated tars which cannot be used in the chlorolysis process as well as all wastewater streams contaminated with traces of chlorinated hydrocarbons are sent to the incineration unit. The waste streams contain chlorinated hydrocarbons (C, H, Cl, O) with possible traces of bromine, iron, copper and aluminum compounds. Combustion air and water also are fed into the combustion chamber. Incineration takes place in the temperature range of 1250°C. Under optimum conditions, the major products resulting from combustion are CO_2, HCl, and H_2O. Trace inorganics present in the feedstock also will be found in the combustion products.

Factors which influence the combustion process are the chlorine content and the oxygen content of the incoming waste streams as well as the quantity of water required. A high chlorine content in the waste streams results in a low heating value for the wastes. A waste stream with a 60 percent to 70 percent chlorine content has a heating value range of 8,400 kJ/kg (3600 Btu/lb) to 16,800 kJ/kg (7200 Btu/lb). Proper combustion of the wastes is difficult when the heating value is below 12,600 kJ/kg (5400 Btu/lb). Therefore, supplemental fuel is needed for combustion. This supplement may be either fuel oil mixed with the incoming waste stream or a separate gas burner.

The combustion product is a gaseous mixture of N_2, O_2, HCl, CO_2, CO, Cl_2, and H_2O. Temperature and residence time of the reactants in the incinerator also are critical parameters. High temperatures permit short residence time, provided that complete combustion (greater than 99 percent) of the chlorinated hydrocarbons is assured with the minimum formation of free chlorine. These results are achieved by a residence time greater than three seconds in the combustion zone and by the introduction of a relatively large quantity of water. It is necessary to add water to the waste streams having a high heating value to regulate the combustion temperature. For this reason, the smaller wastewater streams are combined with additional water to reduce the combustion temperatures from approximately 2000°C to approximately 1250°C. (Temperature reduction also is needed to protect the materials used in the combustion chamber.) The ratio of hydrogen chloride to chlorine also increases with rising

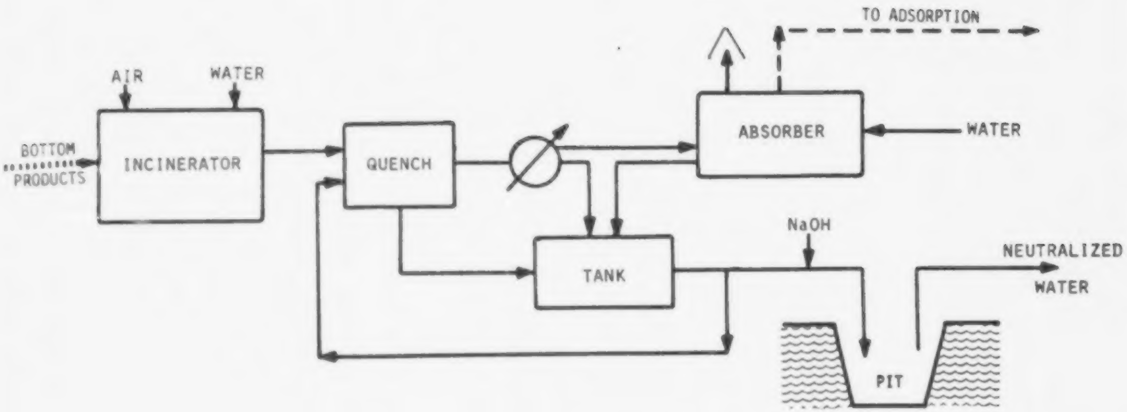
TO ADSORPTION
AIR
WATER
BOTTOM PRODUCTS
INCINERATOR
QUENCH
ABSORBER
WATER
NaOH
TANK
NEUTRALIZED WATER
PIT

Figure 6. Incineration section

temperature as the destruction of chlorinated hydrocarbons is improved at high temperatures. Excessive oxygen affects the reactions as the free chlorine content in the exhaust gas is increased. A lack of oxygen results in the formation of soot. An excess of water also suppresses the formation of free chlorine.

The exit gases from the combustion unit are discharged through a cooler to a quench system and a scrubbing system. In the quench system, the temperature of the gases is lowered from approximately 1000°C to approximately 100°C by the injection of recycled hydrochloric acid. The quench gas is fed to the scrubber, where HCl is absorbed. Emissions from the scrubber are 143 gm per hour of HCl. Additional HCl is collected in the bottom portion of the scrubber. From here, a portion of the HCl is recycled to the quench system (see above) with the remainder neutralized in a pit and sent to storage. If there were perfect combustion in the incinerator, no free chlorine would be formed so that the HCl could be removed thoroughly with water. With incomplete combustion, Cl_2 may be emitted in ppm quantities if the off-gas is washed only with water. To prevent the venting of excessive quantities of Cl_2 to the atmosphere, a small amount of caustic soda is added to the wash water, to enhance removal of the HCl formed as well as to eliminate most Cl_2 traces. With caustic added, the wastewater effluent may contain sodium chloride (NaCl), sodium hypochlorite (NaOCl), sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), sodium bromide (NaBr), and sodium hypobromite (NaOBr). Sodium bromide and sodium hypobromite are present because of the presence of trace amounts of bromine in the feedstock. Typical discharges are shown in Table 29.

Absorption System (See Figure 7)

An absorption unit is provided to treat the waste vent gases which contain chlorine, hydrogen chloride, and carbonyl chloride. Waste gases are released during a plant shutdown as a result of the pressure relief needed in the safety valve. Gases also are released when filters are changed. The absorption units consist of four stages in which absorption takes place in liquid scrubbers by recirculation of a 20 percent NaOH solution. The reactions taking place are exothermic, therefore, cooling units follow the scrubber. Compounds vented

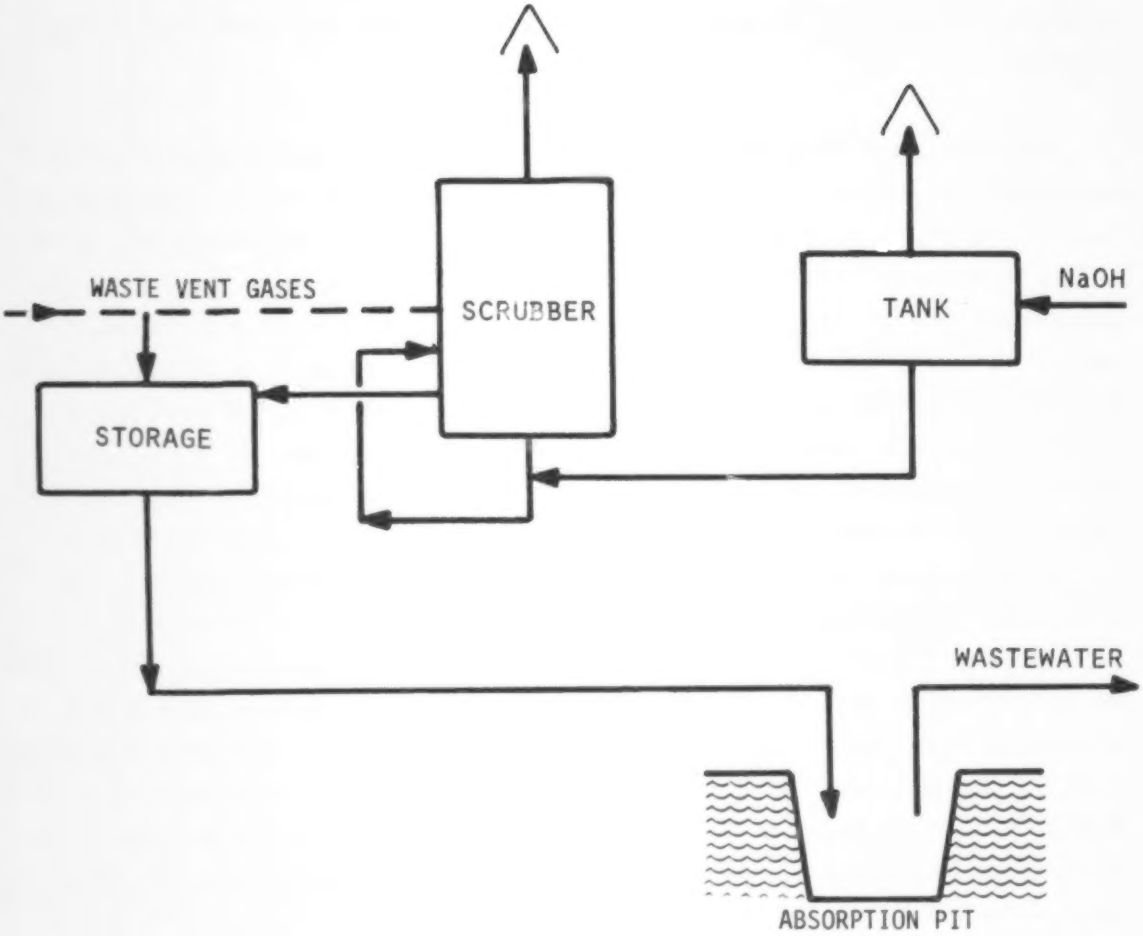
WASTE VENT GASES
SCRUBBER
TANK
NaOH
STORAGE
WASTEWATER
ABSORPTION PIT

Figure 7. Absorption section.

TABLE 29. WASTEWATER DISCHARGES FROM INCINERATION PIT

Pollutant	Discharge Rate
NaCl	700 kg/hr
NaOH	traces
NaOCl	traces
Na_2CO_3	traces
NaBr	traces
NaOBr	traces

to the atmosphere from the scrubbers are shown in Table 30. The NaOH overflows from the scrubbers into a wastewater pit from which it is discharged to a wastewater purification plant. The compounds going into the purification plant are shown in Tables 31 and 32.

The absorption system includes intermediate storage of a large amount of bleaching liquor to be treated in the wastewater purification plant. This provision is necessary in view of the fact that the capacity of the wastewater purification plant would not be sufficient in case of instantaneous discharge of the NaOH from the emergency absorption tanks. Estimated emissions from the hold tank are 3 gm per hour of SO_2.

Total Air and Water Emissions

The total air emissions from the Hoechst-Uhde process are shown in Table 33. The total water discharges under normal flow conditions are shown in Table 34.

Malfunction Potential

In the chlorolysis process, most process components are in a parallel or back-up configuration which allows the entering stream to be diverted if a problem arises. This helps avoid costly shut-down of the operation. A listing of some possible operational malfunctions is shown in Table 35. The

TABLE 30. MAXIMUM EMISSIONS FROM THE ABSORPTION UNIT FOR CHLOROLYSIS PROCESS, BASED UPON 25,000 METRIC TONS/YEAR

Pollutant	Emission Rate, gm/hr
Cl_2	30.6
$COCl_2$	42.6
CCl_4	66.3

TABLE 31. WASTEWATER DISCHARGES FROM ABSORPTION PIT

	Conditions	
Pollutant	Normal Flow, kg/hr	Maximum Flow, kg/hr
NaOH	2.0 to 4.0	6.4
NaOCl	0.8	0.4

TABLE 32. WASTEWATER DISCHARGES FROM ABSORPTION PIT IN EMERGENCY SITUATIONS

	Conditions	
Pollutant	Normal Flow, kg/hr	Maximum Flow, kg/hr
NaCl	1000	500
Na_2CO_3	<50	50
CCl_4	—	400
Heavy ends	—	100

TABLE 33. TOTAL AIR EMISSIONS FROM THE CHLOROLYSIS PROCESS

Pollutant	Emission Rate
CCl_4	67.01 gm/hr
$COCl_2$	42.82 gm/hr
HCl	4.42 kg/hr
Cl_2	31.03 gm/hr
SO_2	3.00 gm/hr

TABLE 34. TOTAL WASTEWATER DISCHARGES FROM THE CHLOROLYSIS PROCESS UNDER NORMAL FLOW CONDITIONS

Pollutant	Emission Rate, kg/hr
NaCl	700
NaOH	2.0 to 4.0
NaOCl	1

TABLE 35. POTENTIAL OPERATIONAL MALFUNCTIONS AT A CHLOROLYSIS PLANT

Operation	Possible Malfunction	Consequence
Waster Transfer to Holding Tank	1) Overfill	Waste Spill
	2) Leakage Due to Seals, Packings, Corrosion	Waste Spill
Waste Transfer to Pretreatment	1) Leakage Due to Seals, Corrosion	Waste Spill
	2) Filter Plugging	None if switched on High Discharge Pressure Overflow to Absorption Section
Incineration	1) Flameout	Toxic Vapor Discharge
	2) Improper Fuel Rate	Excess Water in Discharge
	3) Improper Air/Fuel Ratio	Inefficient Combustion
	4) Injection into Cool Combustion Zone on Startup	Inefficient Combustion
Scrubbing	1) Circulating Pump Failure	High HCl Concentrations in Vent Gas Solution Spill
	2) Pump, Valve or Tank Leak	

most likely consequence of a malfunction would be a waste spillage. Spill potentials are greatest in the storage and transfer areas. As these are potentially hazardous substances, the storage/transfer area should be paved and diked with a catch basin to return these materials to a storage tank.

4.3.2 Environmental Impact Analysis

Emission estimates described in the previous section were used as inputs for analytical procedures designed to assess impacts of these emissions on air and water quality. Expected impacts on air quality were determined via the use of air quality simulation models. Estimations of water quality and other impacts were determined via a process of comparing estimated mass emission rates with known and potential environmental effects of the constituent in question.

Air quality simulations were performed for a variety of emission sources within the plant. Process units and corresponding emission constituents are listed in Table 36.

Estimates of emission rates for identified constituents were made in accordance with procedures described earlier in this report. These estimates served as inputs to the air quality simulation model. Simulations were performed for each constituent and process unit listed in Table 36.

TABLE 36. SUMMARY OF CHLOROLYSIS PROCESS UNITS
AND EMISSION CONSTITUENTS

Process Unit	Emission Constituents
HCl Column	CHl, Cl_2, CCl_4, $COCl_2$
NaOH Absorber	HCl, CCl_4, $COCl_2$
Incineration Unit	HCl
Absorption Unit	Cl_2, CCl_4, $COCl_2$
Absorption Tank	SO_2

Other parameters which served as inputs to the air quality simulation were effective stack height, wind speed and stability category. Information was not available to permit an analytical derivation of effective stack heights for the process units considered. Therefore, an effective stack height of 5 meters was assumed for ground level units, and the physical height of the incinerator was used to simulate air quality resulting from emissions from that source. Simulations were based on a wind speed of 4 meters per second and a stability category of D. These meteorological parameters are considered to be representative of the general conditions observable at the hypothetical Houston site.

Selected results of the air quality simulations are presented in Table 37. The values listed were obtained by taking the predicted ground level concentration for each process unit-constituent pair, and summing these concentrations for those constituents which were emitted by more than one process unit. Appendix B provides details of the simulation and presents results of air quality simulations performed for differing distances downwind from the source.

The largest emissions associated with the chlorolysis process were due to venting and fugitive emissions from sources closest to ground level. Consequently, the highest concentrations are expected to occur close to the source. All concentrations listed in Table 37 are predicted to occur at the closest downwind location for which simulations were run (100 meters).

In general, the predicted air concentrations are low with respect to potentially adverse acute effects on exposed human and biological populations. Threshold Limit Values (TLV's) for constituents listed in Table 36 are presented in Table 38. These TLV's are generally two to four orders of magnitude higher than predicted maximum constituent concentrations attributable to all process units (Table 37). There is even a greater difference between the predicted levels and other levels (listed in Table 38) known to produce assorted toxic effects in man and other organisms. Because highest predicted ground level concentrations occur close to the source, plant personnel comprise the population most at risk.

TABLE 37. SUMMARY OF AIR QUALITY SIMULATION RESULTS FOR A CHLOROLYSIS PLANT

Pollutant	Maximum Ground Level Concentration, $\mu g/m^3$
Hydrogen Chloride, HCl	1435
Chlorine, Cl_2	10
Carbonyl Chloride, $COCl_2$	14
Carbon Tetrachloride, CCl_4	22
Sulfur Dioxide, SO_2	1

Hexachlorobenzene (HCB) is a waste by-product of most of the chlorolysis processes currently in use (Reference 21). However, the Hoechst-Uhde process is capable of converting HCB to the process end product, CCl_4.

Emissions from manufacturing, storage and transport of HCB containing materials resulted in livestock contamination within a 100 square mile area of Louisiana (Reference 24). This incident prompted EPA to establish an enforceable tolerance level for HCB in livestock products (Reference 24). Another damage incident involving HCB occurred in Turkey. During the 1950's, 5000 sustained HCB poisoning following ingestion of contaminated grain. Symptoms produced by ingesting this material included liver deterioration, acute skin sensitivity and blistering, excessive hair growth, and for some individuals, tremors, convulsion and death (Reference 24). TLV data was not available for this compound, but the information provided above indicates that any emission of this material deserves close scrutiny.

There were no data available describing emission of particulate matter from the chlorolysis process. Such material may be emitted from the incinerator, but the absence of data on its quantity and nature prevents discussion of expected impacts. However, it should be mentioned that the use of a scrubber should keep such emissions at a relatively low level.

TABLE 38. THRESHOLD LIMIT VALUE AND TOXICITY DATA FOR SELECTED COMPOUNDS EMITTED FROM THE HOECHST-UHDE CHLOROLYSIS PROCESS

Compound	TLV (mg/m^3)	LC_{50} (ppm)	TC_{LO} (ppm)	LD_{50} (mg/kg)	TL_m96 (ppm)
Hydrogen Chloride, HCl	7	3124 Rat/30 min.			
Chlorine, Cl_2	3	293 Rat/1 hr.	15 Human, PUL		< 1 Carp
Carbonyl Chloride, $COCl_2$	0.2	780 Human			
Carbon Tetrachloride, CCl_4	65		20 Human, CNS	1770 Rat, Oral	10-100 Plaice
Sulfur Dioxide	13				

Source: Based on information obtained from References 22 and 23.

Abbreviations used:
TLV : Threshold limit value acceptable levels for 8 hour/day occupational exposure.
LC_{50} : Lethal air concentration for 50% of test animals.
TC_{LO} : Lowest air concentration capable of producing a toxic effect.
LD_{50} : Lethal dose for 50% of test animals.
TL_m96 : Water concentration of a constituent which kills 50% of aquatic test animals in 96 hours of exposure.

PUL : Pulmonary effect.
CNS : Central nervous system effect.

The constituents of the liquid and solid waste streams from the chlorolysis process were listed in Tables 29, 31, and 32. In addition, it is expected that trace elements such as copper, iron, aluminum, and various heavy metals are present in small quantities. Data from Hoechst-Uhde do not indicate the presence of these trace elements in the effluent streams. Therefore, it was assumed that trace elements are present in small quantities as contaminants.

As indicated in the tables, the waste effluent streams are primarily liquid. Any solid emissions would be contained in the liquid effluent as dissolved and/or suspended particles.

The liquid effluents will be discharged to a municipal sewage system after pretreatment. Any residual organic and trace element constituents will most likely be concentrated in the sludges generated by the municipal treatment system. The sludges will probably be landfilled, and the effects of any contaminants deposited onto or into the soil will vary as a function of the type and porosity of the soil, the weather conditions, and the mobility of the individual contaminants. Both organochlorine compounds and various trace elements (e.g., lead and copper) have been found in sanitary fill leachates (Reference 26), so it will be necessary to minimize these types of constituents in the chlorolysis effluents to avoid eventual transfer to the land.

The Resource Conservation and Recovery Act of 1976 (RCRA) requires that the Administrator of the Environmental Protection Agency promulgate standards applicable to owners of hazardous waste treatment, storage, and disposal facilities. These standards include requirements for operating methods, and practices, location and design of facilities, and contingency plans for minimizing unanticipated damage from treatment, storage, or disposal of hazardous waste. In that the chlorolysis processes involve the treatment of hazardous wastes, it is likely that these facilities will be covered by such regulations. Therefore, procedures will be instituted to ensure that all process residues will be handled in a way which is environmentally acceptable.

5. COMPARATIVE COST ANALYSIS AND ENVIRONMENTAL ASSESSMENT

5.1 COST ANALYSIS COMPARISON

The capital investment costs and the unit costs for the disposal of liquid organochlorine wastes by land-based incineration, at-sea incineration, and chlorolysis are compared in Table 39. As discussed previously, costs for land-based incineration were based on a centralized facility similar to the one operated by Rollins Environmental Services in Houston, Texas. Costs for at-sea incineration were based on the M/T Vulcanus. Costs for chlorolysis were based on the Hoechst-Uhde design of a chlorolysis plant located on the Gulf Coast. Unit disposal costs presented for land-based incineration and chlorolysis were calculated at 15% discounted cash flow rate of return.

As noted from Table 39, chlorolysis requires the highest capital investment cost because of the complexity of the plant design to produce saleable products. In terms of unit disposal costs, land-based incineration is considerably more expensive than at-sea incineration, mainly due to the cost of hydrated lime needed for the neutralization of hydrochloric acid, and the higher unit costs for capital related charges and operating labor. The capital investment costs and annual operating costs are similar for a land-based incineration facility and for an incineration ship, but the unit costs are lower for the incineration ship because of the larger volume of organochlorine wastes disposed each year.

The unit cost of disposal of organochlorine wastes by chlorolysis is dependent on the carbon tetrachloride selling price. At the base case of carbon tetrachloride selling at $300 per metric ton, the unit disposal costs by chlorolysis are $33 to $116 per metric ton higher than the corresponding unit disposal costs by at-sea incineration. As compared with land-based incineration, chlorolysis is less expensive for the disposal of the

TABLE 39. COST COMPARISON FOR DISPOSAL OF ORGANOCHLORINE WASTES

Disposal Method	Capital Investment Cost	Annual Volume of Waste Disposed, Metric Tons	Unit Disposal Cost, $/Metric Ton				
			CMW Waste	Perchloro-ethylene Waste	Hexachloro-cyclopentadiene Waste	VCM and Solvent Waste	VCM Waste
Land-based Incineration	$ 4,592,600	23,420	181	212	203	203	193
At-sea Incineration	$ 4,000,000- $ 6,000,000	69,000*	80	91	84	85	80
Chlorolysis	$27,210,000	25,000					
	CCl_4 @ $270 per metric ton		302	216	271	248	240
	CCl_4 @ $300 per metric ton		196	136	196	158	134
	CCl_4 @ $330 per metric ton		90	56	121	68	27

* Annual volume of waste disposed is based on an incinerator feed rate of 23 metric tons per hour and 3,000 hours of incinerator operation per year.

perchloroethylene waste, the hexachlorocyclopentadiene waste, the mixed VCM and solvent waste and the VCM waste, but more expensive for the disposal of the CMW waste. Chlorolysis becomes a less attractive option for the disposal of the CMW waste and the hexachlorocyclopentadiene waste because of the presence of oxygen in these wastes, leading to the formation of carbonyl chloride and a lower yield for carbon tetrachloride. The carbonyl chloride formed is disposed of by incineration. The alternative of purifying carbonyl chloride for usage as feedstock in an isocyanate process is not considered in the present study.

At a carbon tetrachloride selling price of \$330 per metric ton, the unit costs of disposal of organochlorine wastes by chlorolysis are competitive with corresponding disposal costs by at-sea incineration. In general, disposal by chlorolysis is favored over at-sea incineration for organochlorine wastes with higher carbon content and lower hydrogen and oxygen content, such as the perchloroethylene wastes, the mixed VCM and solvent waste, and the VCM waste. This is because carbon present in the organochlorine waste is converted in the chlorolysis process by the addition of chlorine, at \$150 per metric ton, to a higher priced commodity, carbon tetrachloride, at \$330 per metric ton. In contrast, hydrogen present in the organochlorine waste is converted in the chlorolysis process by chlorine, at \$150 per metric ton, to a lower priced commodity, hydrogen chloride, at \$50 per metric ton. Similarly, the oxygen present is converted in the chlorolysis process to carbonyl chloride with no byproduct value.

At a carbon tetrachloride selling price of \$270 per metric ton, the unit costs of disposal of organochlorine wastes by chlorolysis are higher than corresponding disposal costs by land-based incineration.

In Figure 2, the effect of carbon tetrachloride selling price on the unit disposal cost of the mixed VCM and solvent waste and the VCM waste is depicted graphically. It is seen that at a carbon tetrachloride selling price of around \$285 per metric ton, chlorolysis becomes less attractive than land-based incineration for the disposal of these two organochlorine wastes from the cost standpoint. At a carbon tetrachloride selling price of around \$315 per metric ton, chlorolysis becomes increasingly cost competitive with at-sea incineration for the disposal of these two organochlorine wastes. Thus, a fluctuation in carbon tetrachloride selling price of ± 5 percent from the base price of $300 per metric ton could determine whether chlorolysis is the least expensive or the most expensive option for the disposal of organochlorine wastes among the three methods compared here.

The economics of disposal of organochlorine wastes by the three alternatives can also be compared in a different fashion. The unit disposal costs for land-based incineration and chlorolysis could be assumed to be the same as that for at-sea incineration, and the calculated discounted cash flow rate of return (DCFRR) can be compared. Similarly, DCFRR for land-based incineration at the unit disposal cost charged by chlorolysis can be calculated, and compared with the DCFRR for chlorolysis. Comparison of DCFRR is possible except in the case of at-sea incineration, where reliable financial data are not available to perform DCFRR calculations.

In Table 40, the calculated DCFRR for land-based incineration and chlorolysis are compared. First, DCFRR for chlorolysis at the unit disposal cost charged by land-based incineration are presented. The comparison of DCFRR shows that, with the exception of the CMW waste, a higher rate of return on investment can be realized from the disposal of organochlorine wastes by chlorolysis than by land-based incineration.

Second, DCFRR for land-based incineration and chlorolysis at the unit disposal cost charged by at-sea incineration are presented. In this case, the comparison of DCFRR shows that land-based incineration cannot be cost competitive with at-sea incineration, because the net operating cost for land-based incineration, without taking into account any return on investment, is higher than the unit disposal costs charged for at-sea incineration. The DCFRR for land-based incineration are, therefore, all less than 0%. For chlorolysis, the charges for the disposal of organochlorine wastes only represent a fraction of the total annual revenue. By lowering the DCFRR to the 10.8 to 13.4% range, chlorolysis can be made to be cost competitive with at-sea incineration for the disposal of organochlorine wastes.

TABLE 40. COMPARISON OF DISCOUNTED CASH FLOW RATES OF RETURN FOR THE DISPOSAL OF ORGANOCHLORINE WASTES

Disposal Method	Waste Type	Unit Disposal Cost, $/Metric Ton	DCFRR *	
			Land-Based Incineration	Chlorolysis†
Land-based Incineration	CMW Waste	181	15.0 %	14.2 %
	Perchloroethylene Waste	212	15.0 %	17.5 %
	Hexachlorocyclopentadiene Waste	203	15.0 %	15.3 %
	VCM and Solvent Waste	203	15.0 %	16.5 %
	VCM Waste	193	15.0 %	17.0 %
At-sea Incineration	CMW Waste	80	< 0	10.8 %
	Perchloroethylene Waste	91	< 0	13.4 %
	Hexachlorocyclopentadiene Waste	84	< 0	10.8 %
	VCM and Solvent Waste	85	< 0	12.4 %
	VCM Waste	80	< 0	13.2 %
Chlorolysis	CMW Waste	196	17.8 %	15.0 %
	Perchloroethylene Waste	136	< 0	15.0 %
	Hexachlorocyclopentadiene Waste	196	13.5 %	15.0 %
	VCM and Solvent Waste	158	4.7 %	15.0 %
	VCM Waste	134	< 0	15.0 %

* Reliable financial data are not available to compute the DCFRR for at-sea incineration.

† For chlorolysis DCFRR calculations, the carbon tetrachloride selling price is assumed to be $300 per metric ton.

Third, DCFRR for land-based incineration at the unit disposal cost charged by chlorolysis are presented. Again, it is shown that with the exception of the CMW waste, the DCFRR for land-based incineration is lower than the corresponding DCFRR for chlorolysis.

5.2 COMPARISON OF ENVIRONMENTAL IMPACTS

Data resulting from air quality simulations for constituents which have counterparts in the three organochlorine waste disposal processes being considered in this report are summarized in Table 41. This table shows that there are general differences in location and magnitude of expected maximum concentrations, as a result of the differences in emission rates and stack heights used in air quality simulations. Because the most significant emissions from chlorolysis are from process unit ventings, maximum concentrations are observed close to the source. The only process unit for which this is not the case is the incinerator at the chlorolysis plant. However, its contribution of emissions is small, and the overall emission pattern of the units predominate. Emission estimates for chlorolysis were obtained from the Hoechst-Uhde report (Reference 3).

The data in Table 41 also highlight differences in the magnitude of air contaminant concentrations produced by three processes. For land-based incineration, the maximum ground level concentration of hydrogen chloride is several orders of magnitude lower than the Threshold Limit Value (TLV) of 7 mg/m^3. The predicted concentrations of unburned wastes were conservatively based on a destruction efficiency of 99.99%, whereas no emission of unburned wastes from the stack was detected in actual tests. Emissions from land-based incineration are, therefore, lower than those expected to cause significant impacts.

For at-sea incineration, emissions of hydrogen chloride are greater than those from the other two processes because of the absence of scrubbers. However, the maximum ambient concentration of hydrogen chloride, at 4.4 mg/m^3, is still below the TLV. The predicted maximum ambient level of unburned wastes, based on a destruction efficiency of 99.99%, is 0.69 μg/m^3. Analysis

TABLE 41. COMPARABLE GROUND LEVEL/SEA LEVEL CONCENTRATIONS OF EMISSIONS FROM LAND-BASED INCINERATION, AT-SEA INCINERATION AND CHLOROLYSIS*

Distance (Meters)	Land-Based Inciner-ation	At-Sea Inciner-ation	Chloro-lysis	Land-Based Inciner-ation	At-Sea Inciner-ation	Chloro-lysis	Land-Based Inciner-ation	At-Sea Inciner-ation	Chloro-lysis†	Land-Based Inciner-ation	At-Sea Inciner-ation	Chloro-lysis
	HCl, μg/m^3			Unburned Waste, μg/m^3			Other Inorganics, μg/m^3			Trace Metals (Ti,Ni,Cr), ng/m^3		
100	---	---	1,434.60	---	---	22.46	---	---	25.76	---	---	NO DATA
200	---	---	529.93	---	---	8.30	---	---	9.51	---	---	
300	---	---	264.34	---	---	4.13	---	---	4.75	---	---	
400	---	---	178.05	---	---	2.78	---	---	3.19	---	---	
500	---	---	127.06	---	---	1.98	---	---	2.27	---	---	
600	---	.10	89.95	---	---	1.39	---	---	1.60	---	.04	
700	.01	.84	74.89	---	---	1.16	.01	---	1.33	.03	.38	
800	.03	8.09	56.10	.01	---	0.87	.04	.04	1.00	.06	3.65	
900	.06	25.43	48.51	.02	---	0.75	.07	.13	0.85	.12	11.49	
1,000	.15	144.67	39.98	.05	.02	0.61	.17	.74	0.70	.33	65.39	
2,000	.50	2,082.66	14.98	.16	.32	0.23	.55	10.59	0.26	1.11	941.31	
3,000	.54	2,849.86	8.25	.18	.60	0.12	.62	19.58	0.15	1.23	1,740.05	
4,000	.49	4,422.80	5.40	.16	.69	0.08	.56	22.49	0.09	1.14	1,999.01	
5,000	.43	4,389.32	3.89	.14	.68	0.04	.49	22.32	0.07	.99	1,983.87	
6,000	.37	4,116.79	2.97	.12	.64	0.04	.42	20.93	0.05	.84	1,860.69	
7,000	.32	3,777.38	2.37	.11	.59	0.03	.37	19.21	0.04	.75	1,707.30	
8,000	.28	3,438.65	1.95	.09	.53	0.02	.32	17.48	0.03	.63	1,554.19	
9,000	.24	3,124.50	1.63	.08	.49	0.02	.28	15.89	0.03	.57	1,412.20	
10,000	.22	2,843.01	1.39	.07	.44	0.01	.25	14.46	0.02	.51	1,284.98	
20,000	.09	1,318.93	0.51	.03	.20	---	.10	6.71	---	.21	596.13	
30,000	.05	781.14	0.28	.02	.12	---	.06	3.97	---	.12	353.06	

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[*] Detailed information on the emission rates, meteorological conditions, and stack heights used in the air quality simulation calculations is presented in Appendix B. Fugitive emissions were not included in the emission rate estimates.

[†] Other inorganics for chlorolysis is sum of Cl_2, SO_2 and $COCl_2$ ground level concentrations.

of ocean water samples obtained in the vicinity of plume touchdown has shown that there was no significant difference in pH and copper (the most abundant heavy metal constituent of the waste burned) as compared with samples from control areas. Organochlorine wastes were not detected at the 0.5 ppb level. It may, therefore, be concluded that emissions from at-sea incineration are not expected to cause major environmental impacts.

For chlorolysis, the predicted maximum ground level concentrations of hydrogen chloride, chlorine, carbonyl chloride, carbon tetrachloride, and sulfur dioxide are all several orders of magnitude lower than their respective TLV's. Emissions from chlorolysis are lower than those from at-sea incineration, and also lower than those from land-based incineration with the exception of hydrogen chloride emissions. Environmental impacts associated with the chlorolysis process should, therefore, be lower than those associated with the other two disposal processes.

Table 42 presents wastewater discharge rates for land-based incineration and the chlorolysis process. This information indicates that much greater water quality impacts (in terms of TDS) may result from land-based incineration, than would be expected from the chlorolysis process. It should also be pointed out that although there are no direct wastewater discharges from at-sea incineration, the spill potential may be higher than the other two disposal processes, especially during the loading operation when hatches are open, samples are being taken, and exposed flex lines are under pressure.

TABLE 42. COMPARISON OF WASTEWATER EMISSIONS FROM LAND-BASED INCINERATION, AT-SEA INCINERATION AND CHLOROLYSIS

Pollutant	Land-Based Incineration (kg/hr)	At-Sea Incineration	Chlorolysis (kg/hr)
Cl^-	1,880	No discharge	425
Na^+	---	No discharge	277
Ca^{++}	1,740	No discharge	---
Organics	Negligible	No discharge	Negligible

5.3 INTEGRATION OF ANALYSIS RESULTS

The results of the present study have indicated that at-sea incineration, at $80 to $91 per metric ton, is the least costly option for the disposal of liquid organochlorine wastes. Chlorolysis has a cost advantage over land-based incineration for the disposal of most organochlorine wastes, and can be made to be cost competitive with at-sea incineration if a DCFRR in the 10.8% to 13.4% range is considered to be acceptable. On the negative side, the economic attractiveness of chlorolysis is very dependent on the selling price for carbon tetrachloride. Because of the uncertain market demand for carbon tetrachloride, there is a higher risk factor associated with capital investment in a chlorolysis plant.

From the environmental impact standpoint, maximum downwind concentrations of inorganic chloride and organochlorine species and particulates emitted from land-based incineration and chlorolysis are all several orders of magnitude lower than their respective Threshold Limit Values (TLV's) or are within air quality standards. Wastewater discharges from both disposal processes have high TDS. For at-sea incineration, maximum downwind concentrations of all species emitted are less than their TLV's, and water quality is not measurably impacted. All three disposal processes can, therefore, be considered as environmentally acceptable. The chlorolysis process, however, has an apparent ecological advantage in that chemical wastes are recycled to yield saleable products. The results should be an environmental credit for an emission that can be avoided, related to the quantities of carbon tetrachloride that would not have to be manufactured by the chemical industry.

In terms of environmental risks associated with operational malfunctions, the greatest spill possibility at a land-based incineration facility exists in the storage tank and transfer. The greatest spill possibility related to at-sea incineration occurs during loading. The other major failure cause for both land-based and at-sea incineration could come from incinerator malfunctions, such as burner flameout. By comparison, the Hoechst-Uhde chlorolysis design is considerably more complex from an equipment standpoint. Increased complexity generally leads to increased reliability problems, but the use of redundant equipment and maintenance surveillance associated with general chemical plant practice will minimize equipment failure problems.

Aside from cost and environmental consideration, land-based incineration has greater versatility in handling different types of wastes. At a land-based incineration facility, the rotary kiln system can be used to handle sludges, solids, semi-solids and contaminated containers as well as liquid wastes. Also, the minimum quantity of waste accepted for disposal at any one time could be a 55-gallon drum or less. Unit disposal costs are generally charged on a cost sharing basis. At-sea incineration is applicable to the disposal of liquid organic wastes as well as aqueous wastes contaminated with organics. The acceptability of burning solids at-sea, on the other hand, remains to be demonstrated. For at-sea incineration, another restriction is that the minimum quantity of waste to be disposed would be one or two shiploads at a time. This means that a storage depot for waste collection would have to be set up if at-sea incineration is to become an available option for the disposal of small quantities of wastes. Disposal by chlorolysis is limited to organochlorine wastes relatively free of particulates, with sulfur content less than 25 ppm, containing no nitrogen or phosphorus, and a maximum of 5 percent aromatic hydrocarbons. Only approximately 10 percent of the organochlorine wastes generated in the U.S. are available and considered as suitable feedstocks for chlorolysis.

Overall, it may be concluded that land-based incineration, at-sea incineration, and chlorolysis are all viable options for the disposal of liquid organochlorine wastes. Chlorolysis should be considered if suitable feedstocks are available and the selling price for carbon tetrachloride remains relatively stable, mainly because it is a recycling process that conserves resources and causes minimum environmental impact. At-sea incineration is cost-effective for the disposal of large quantities of liquid organochlorine wastes, and the environmental risks are considered to be acceptable. Land-based incineration, although relatively more expensive, is suited for the disposal of other types of liquid wastes as well as solid wastes, with no restraints on the minimum quantity accepted for disposal.

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APPENDIX A

CALCULATION OF UNIT COST OF DISPOSAL OF ORGANOCHLORINE WASTES

The method used for estimating the unit cost of disposal of organochlorine wastes is based on the discounted cash flow (DCF) technique. In essence, this technique determines the annual revenue during the plant life which will generate a discounted cash flow equal to the total capital invested for the plant. In DCF analysis, all future net income is discounted to a present value depending on the discounted cash flow rate of return (DCFRR). Discounting can also be done on either an annual or continuous basis. For the present situation, it is more reasonable to assume that transactions will occur throughout the year and not in one lump sum, and therefore continuous discounting is more representative of the actual flow of funds.

The DCF method used to derive the unit disposal cost equation follows the procedure described by Uhl (Reference A-1). The basis for the analysis include the following:

- 10 year plant life with no salvage value at the end of life of the plant.
- Straight line method to calculate annual depreciation.
- Negligible land cost.
- Startup cost is expensed uniformly during the first year of operation and not treated as capital investment. Also, startup cost is assumed to be 5% of total plant cost.
- Interest on construction is considered as an operating expense at the end of the first year. Also, interest is charged on only the fraction of the construction cost that corresponds to the debt fraction of the total capitalization for the company. This is assumed to be 30%. Interest is at 10% rate.
- Working capital is assumed to be 15% of annual revenue.
- Annual revenue and operating cost are assumed to be constant during the plant life.

- Income tax rate is 50%.

- Uniform continuous discounting factors are used for depreciable investment, startup cost, and cash flow.

- Instantaneous continuous discounting factors are used for interest during construction (a one-time expense at the end of the first year) and for recovery of working capital (at the end of 10 years).

Definition of Terms

I = Total plant cost, \$. Because interest during construction and startup costs are expensed, this is also the total depreciable investment.

W = Working capital, \$.

U = Startup cost, \$.

C = Net annual operating cost, \$.

S = Annual revenue, \$.

D = Annual depreciation, \$. With 10 year straight line depreciation, $D = 0.1\ I$.

CF = Annual cash flow, \$.

t = Income tax rate = 0.5.

G = Annual quantity of organochlorine waste disposed, metric tons.

R = Discounted cash flow rate of return.

Annual Cash Flow

$$\begin{aligned} CF &= D + (1 - t)(S - C - D) \\ &= 0.1I + 0.5(S - C - 0.1I) \\ &= 0.5S - 0.5C + 0.05I \qquad \text{(A-1)} \end{aligned}$$

Interest During Construction

It is assumed that interest is paid on 30% of the total plant cost, or 0.3I. The interest factor to be applied is found from the following schedule to be 0.2234. Interest is paid at the end of the first year (Reference A-1).

Years Before Start-Up	Project Expenditure Schedule		Interest Factor at 1 yr. at 10% Cost Interest		Weighted Interest Factor
Second (-2 to -1)	50%	X	1.2846	=	0.6423
First (-1 to 0)	50%	X	1.1623	=	0.5811
					1.2234

The actual interest payment is 0.2234 X 0.3 I = 0.06702 I.

Calculation of Unit Disposal Cost

From the calculations summarized in Table A-1, Total Discounted Cash Flow =

$$-(e^{2R}-1)\ I/2R - W - 0.030321\ I - 0.5\ (1 - e^{-R})\ U/R + (1 - e^{-10R})\ CF/R + e^{-10R}\ W = 0 \qquad \text{(A-2)}$$

Substituting the value of CF from equation (A-1) into equation (A-2) and simplifying

$$S = C + \left(\frac{e^{2R} - 1}{1 - e^{-10R}} + \frac{0.060642R}{1 - e^{-10R}} - 0.1\right) I + 2RW + \frac{1 - e^{-R}}{1 - e^{-10R}} U \qquad \text{(A-3)}$$

or $S = C + aI + bW + cU$ (A-4)

where

$$a = \frac{e^{2R} + 0.060642\ R - 1}{1 - e^{-10R}} - 0.1 \qquad \text{(A-5)}$$

$$b = 2R \qquad \text{(A-6)}$$

$$c = \frac{1 - e^{-R}}{1 - e^{-10R}} \qquad \text{(A-7)}$$

Therefore

$$\text{Unit Disposal Cost (\$/metric ton)} = \frac{C + aI + bW + cU - S'}{G} \qquad \text{(A-8)}$$

The values of the constants a, b and c at different discounted cash flow rates of return are given in Table A-2. S' is the annual revenue derived from the sale of products generated from the processing of wastes.

Simplified Calculation of Unit Disposal Cost

With the additional assumptions that the startup cost U is equal to 5% of the investment I, and the working capital W is equal to 15% of the annual revenue S, equation (A-4) can be further simplified to:

$$S = \frac{a + 0.05\,c}{1 - 0.15\,b} I + \frac{1}{1 - 0.15\,b} C = \alpha I + \beta C \tag{A-9}$$

Therefore

$$\underset{(\$/\text{metric ton})}{\text{Unit Disposal Cost}} = \frac{\alpha I + \beta C - S'}{G} \tag{A-10}$$

The values of the constants α and β at different discounted cash flow rates of return are also given in Table A-2. Equation (A-10) is used in calculation of the unit cost for the disposal of organochlorine wastes.

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TABLE A-1. CALCULATION OF DISCOUNTED CASH FLOW

Time, Year	Item	Investment	Cash Flow	Discounting Factor	Discounted Cash Flow
-2 to 0	Depreciable Investment	I		$(e^{2R} - 1)/2R$	$-(e^{2R} - 1)\ I/2R$
0	Working Capital	W		1.0	$-W$
1	Interest on 30% of Total Plant Cost at 10% Rate		$-0.5^{*} \times 0.06702I$	$e^{-0.1}$	$-0.030321\ I$
0 to 2	Start-up Cost		$-0.5^{*}\ U$	$(1 - e^{-R})/R$	$-0.5\ (1 - e^{-R})\ U/R$
0 to 10	Cash Flow		10 CF	$(1 - e^{-10R})/10R$	$(1 - e^{-10R})\ CF/R$
10	Recover Working Capital	$-W$		e^{-10R}	$e^{-10R}\ W$

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[*] The actual cash flow for these two items so designated are reduced by 50% due to the effect on Cash Flow of income tax.

TABLE A-2. VALUE OF CONSTANTS UTILIZED IN THE CALCULATION OF UNIT DISPOSAL COST BY THE DCF METHOD

DCF Rate of Return	Value of Constants				
	a	b	c	α	β
10%	0.25985	0.20	0.15054	0.27565	1.03093
12%	0.29857	0.24	0.16182	0.31811	1.03734
15%	0.36205	0.30	0.17930	0.38850	1.04712
18%	0.43222	0.36	0.19735	0.46732	1.05708
20%	0.48283	0.40	0.20964	0.52480	1.06383

APPENDIX B

AIR QUALITY SIMULATION METHODOLOGY

A computer simulation of air quality impacts that would result from at-sea incineration, land-based incineration and the chlorolysis process was performed using the most representative set of physical parameters and meteorological conditions that could be determined from the available data. In this appendix the formation of the model is presented and the inherent limitations of the analysis are discussed. The values of the input data are given and the results of a sensitivity analysis performed for two parameters are shown. The results of the air quality simulation are presented and the air impacts associated with at-sea and land-based incineration and chlorolysis are briefly discussed.

TECHNICAL APPROACH

Downwind concentration of gaseous pollutants can be simulated with a conventional Gaussian diffusion plume model which assumes a continuous point source of strength Q. The basic equation used in the calculation is:

$$\chi\ (x,y,z) = \frac{Q}{2\pi u\ \sigma_y\ \sigma_z} \exp\left[-\ y^2/2\ \sigma_y{}^2\right]\{\exp\left[\ -\ (z-h)^2/2\ \sigma_z{}^2\ \right] + \exp\left[\ -(z+h)^2/2\ \sigma_z{}^2\ \right]\} \qquad \text{(B-1)}$$

where $\chi(x,y,z)$ is the concentration downwind from the source at x,y,z; Q is the continuous point source strength (i.e., emission rate); h is the effective stack height; u is the mean wind speed; and σ_y and σ_z are the horizontal and vertical standard deviations of the plume. In the above formulation the x-axis is aligned with the mean wind speed, the y-axis is in the crosswind direction, and the z-axis is in the vertical.

To obtain the downwind concentration at ground level, equation (B-1) simplifies to

$$\chi(x,o,o) = \frac{Q}{\pi u\ \sigma_y\ \sigma_z} \exp\left[\ -\ \frac{1}{2}\left(\frac{h^2}{\sigma_z{}^2}\right)\right] \qquad \text{(B-2)}$$

When gases and particulates are released from a point source they are carried downwind and are dispersed by atmospheric turbulence. Particulates will have an additional downward component of velocity at their terminal velocity, v_s. As the gases or particulates approach the ground a fraction will be deposited on the surface or on vegetation by direct sedimentation, inertial impaction, adsorption, chemical reaction and other mechanisms. This removal causes the downwind flux of airborne gases or particulates to decrease. In the conventional Gaussian plume model described in Equation (B-1), no account is made for gravitational settling of particulates or for deposition mechanisms.

Overcamp (Reference B-1) has proposed a modification of the Gaussian plume model for the deposition of fine and heavy particulates and gases. It combines a downward-sloping plume to account for settling and the assumption of a constant deposition velocity. The general equation for the concentration is

$$\chi(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[- y^2/2\,\sigma_y{}^2 \right] \{\exp\left[-(z-h+\frac{v_s x}{u})^2/2\,\sigma_z{}^2\right]$$

$$+ \quad \alpha\{x'\} \;\exp\left[-(z+h-\frac{v_s x}{u})^2/2\,\sigma_z{}^2\right] \} \qquad \text{(B-3)}$$

where $\alpha\{x'\}$ could be considered as that fraction of the plume that is reflected at the surface and $\alpha\{x'\}$ is defined as

$$\alpha\{x'\} = 1 - \left[\frac{2v_d}{v_s + v_d + (uh - v_s x')\,(\sigma_z)-1\,(d\sigma_z/dx)} \right] \qquad \text{(B-4)}$$

where v_d is the deposition velocity and v_s is the terminal settling velocity. For a gas that is perfectly reflected at the ground, α is unity. It should be noted that x' is the point where the plume image streamline passes through the ground plane. An implicit equation for x' is

$$z+h - \frac{v_s x}{u} = (h - \frac{v_s x'}{u}) \; \frac{\sigma_z(x)}{\sigma_z(x')} \qquad \text{(B-5)}$$

The air quality simulation results presented in this report were not able to incorporate particulate settling or deposition mechanisms due to the unavailability of specific data. Particle size and the characteristics of the surface, among other parameters, would need to be known before settling and deposition could be included in the analysis. Therefore, ground-level downwind concentrations were calculated from Equation (B-2) using the most representative set of physical parameters and meteorological conditions that could be determined from the available data.

A word needs to be said about the diffusion and transport of pollutants over large bodies of water. It has been long known that the turbulence spectrum (and hence the diffusion) over water is different from that over land (References B-2 and B-3) at comparable stabilities. Raynor et a. (Reference B-4) reported diffusion observations at sea which showed little spreading and marked departure from the standard Pasquill-Gifford curves. This apparently occurs for two reasons. First, the ocean surface is a dynamic one in contrast to the static land surface. Therefore, the roughness height, z_0, which among other parameters determines the turbulence intensity, becomes a function of the stage of wave development. Kitaigorodskii (Reference B-5) derived expressions from determining an "equivalent sand roughness" element, z_s, of the sea surface. This value was found to be dependent on the Reynold's number at the surface. Second, density stratification over water is controlled not only by heat flux but also by water vapor flux because of the intense evaporation which takes place at the water surface. Monin (Reference B-6) has taken this into account by redefining the stability parameter, L, in terms of the latent heat of vaporization, the Bowen ratio and the L which would occur over land.

Gifford (Reference B-7) suggested in principle a method for obtaining the equivalent Pasquill-Gifford stability over water. He suggested that the z_s and L over water be first found, then the equivalent Pasquill-Gifford turbulence level be found from either Golder's (Reference B-8) or Smith's (Reference B-9) nomograms. Using values characteristic of the ocean, it was found that L could range anywhere between 20-40% of its "equivalent over-land" value, confirming the greater stability of the air mass over the ocean.

Portelli (Reference B-10) recently reviewed the subject of diffusion over water. The turbulence intensity of the atmosphere over the ocean was found to depend on (1) the temperature difference between the air and the ocean surface, and (2) the roughness of the ocean surface. It was difficult, however, to obtain quantifiable results (in particular for σ_y and σ_z) over the ocean which could be compared with the equivalent land values. Therefore, in this report, the at-sea values for these diffusion parameters were assumed to be the same as the corresponding land values.

LIMITATIONS OF THE ANALYSIS

There are a series of inherent problems and other factors which could have significant effects on the nature and applicability of results from this type of simulation analysis. In this section these problems and factors will be identified and measures taken (if any) to mitigate their effects will be described.

The first problem involves inter-facility variations of those factors that affect effective stack height. Factors of importance include the following:

(1) The physical height of the stack's terminus above ground level (or sea level for ships)

(2) The ambient temperature lapse rate, effluent velocity, temperature of the effluent, and stack radius.

Numerical studies (e.g., see the sensitivity analysis performed in a later section of this appendix) have shown that ground level concentrations are strongly dependent on effective stack height. There is no simple way of designing this analysis to reflect these individual differences; therefore, the results in this report should be viewed as approximate concentrations expected to occur under the conditions imposed by a set of specified input parameters.

A second problem relates to differences in the meteorological conditions that may exist at individual facilities. Predicted ambient concentrations are strongly dependent on the selected meteorology. Atmospheric mixing over the ocean is generally conceded to be less than that over land, but the exact quantities are not yet known. As with the previous problem, there is no way of determining meteorological conditions that would be universally representative of at-sea and land-based conditions. However, information is presented in the model input sections of this appendix which shows that the selection of meteorological parameters is validated to some extent by available data. The simulation was performed under a set of conditions which were considered to be the most representative of the land-based and at-sea facilities. It was assumed that these conditions would persist over long averaging times (on the order of 24 hours), even though such a persistance is highly unlikely. In addition, other special meteorological circumstances (fumigation, looping and trapping) may also be conducive to high pollution build-ups especially around the land-based site.

Another level of difficulty stems from a void in our knowledge of aerosol scavenging and chemical reaction of pollutants in the atmosphere. Hydrogen chloride by virtue of its deliquescent nature, can be expected to be absorbed by moisture typically present in marine environments. HCl may also combine with other salt complexes and condensation nucleii present over the ocean. Similarly, unburned wastes and total organics may themselves enter into chemical reactions with marine aerosols or, at the very least, provide nucleation centers (condensation nucleii) for droplet formation. A determination of the consequences of the types of chemical reactions and the resulting scavenging of combustion products is beyond the scope of this study. However, in this analysis it is assumed that no scavenging takes place.

MODEL INPUT

The inputs to the diffusion model used for the air quality simulation in this report were the following:

- Emission or discharge rate
- Effective stack height
- Atmospheric stability category
- Wind speed

The emission rates used as inputs to the model are shown in Table B-1(a) for at-sea and land-based incineration and in Table B-1(b) for the chlorolysis process. The emission rates for at-sea and land-based incineration were obtained from actual test data measured during operation of the incinerator (References 4, 5, 9 and 11). Emission rates for the chlorolysis process were obtained from Reference 3.

The physical stack height of the land-based incineration facility is 30 meters. The approximate distance of the top of the stack above the waterline for the at-sea facility is 15 meters. Effective stack height values were calculated to be 96.5 meters for the land-based facility and 125.5 meters for the at-sea facility. For the chlorolysis process, the physical stack height of 40 meters in the Hoechst-Uhde design was used as the effective stack height for the incineration unit (Reference 3). A value of 5 meters was used as the effective stack height for all other units that discharged emissions because these are all emissions from process unit ventings.

TABLE B-1(a). EMISSION RATES USED FOR AIR QUALITY SIMULATION FOR AT-SEA AND LAND-BASED INCINERATION[a]

Constituent	Emission Rate (kg/hr) At-Sea Incineration	Land-Based Incineration
HCl	14.16×10^3	0.895
Unburned Wastes[b]	8.8 (99.96% DE[c]) 2.2 (99.99% DE[c])	0.3
Inorganics	72.0 53.0	
Particulates		1.03
F	1.0	
Cr	4.0	6.9×10^{-4}
Ni	2.0	6.9×10^{-4}
Ti	0.4	6.9×10^{-4}
Pb	0.4	
Cu	0.7	
Zn	0.7	
As	0.1	
Co	0.1	

[a] Emission rates are based on sampling and analysis data obtained at two operating facilities (References 4, 5, 9 and 11). See Sections 3 and 4 of this report for a detailed description of how emissions were determined.

[b] The magnitude of this emission is determined by the use of combustion efficiency for the at-sea facility and detection limits for the land-based facility. See Sections 3 and 4 of this report.

[c] DE = Destruction Efficiency

TABLE B-1(b). EMISSION RATES USED FOR AIR QUALITY SIMULATION FOR THE CHLOROLYSIS PROCESS

NaOH Absorber	Inerts	10 kg/hr
	CCl_4	0.5 gm/hr
	$COCl_2$	0.01 gm/hr
	HCl	0.03 gm/hr
Incineration Unit	Inerts	2737 kg/hr
	HCl	142.6 gm/hr
Absorption Unit	Inerts	1250 kg/hr
	Cl_2	30.6 gm/hr
	$COCl_2$	42.6 gm/hr
	CCl_4	66.3 gm/hr
Absorption Tank	SO_2	3.0 gm/hr
HCl Column	HCl	4.28 kg/hr
	Cl_2	0.43 gm/hr
	CCl_4	0.21 gm/hr
	$COCl_2$	0.21 gm/hr

Table B-2 shows the annual percent frequency of Pasquill categories for all wind directions and speeds at seven cities across the United States. The D stability (neutral) is the most commonly occurring, while the A category (highly unstable) is the least. All simulations were performed for neutral (Class D) atmospheric stabilities.

TABLE B-2. ANNUAL PERCENT FREQUENCY OF PASQUILL STABILITY CATEGORIES FOR ALL WIND DIRECTIONS AND SPEEDS

	Pasquill Stability Category					
	A	B	C	D	E	F
Birmingham, Alabama	1	7	12	44	36*	
Tucson, Arizona	2	10	14	33	41*	
Los Angeles, Calif.	0	4	15	48	13	19
Miami, Florida	0	5	14	42	39*	
Chicago, Illinois	1	5	11	55	12	17
New York, New York	0	3	10	67	13	6
Philadelphia, Pa.	0	5	11	51	14	18

*Indicates E and F categories combined. (After Reference B-11).

A mean wind speed of 4.0 meters per second was used in all simulations. Table B-3 summarizes average wind speeds and directions for three on-shore sites closest to the North Atlantic area under consideration as a site for at-sea incineration. Averages at these three sites were 4.0 meters per second at Trenton, 4.6 meters per second at Newark and 4.8 meters per second at Atlantic City. The value of 4.0 meters per second was selected because the use of this value would result in higher ground level concentrations. (See Sensitivity Analysis in the next section of this Appendix). Table B-4 shows the average wind speed and direction for Houston over a period of 32 years. The average over 32 years was 4.8 m/s while for 1969 the average was 3.5 m/s. Again a value of 4.0 m/s (rather than 4.8 m/s) was selected as this would result in higher ground level concentrations.

TABLE B-3. AVERAGE WIND SPEEDS (METERS/SECOND) AND PREVAILING WIND DIRECTION FOR THREE COASTAL AREAS

	Atlantic City[a]		Newark[b]		Trenton[c]	
	Speed Meters/Second	Direction	Speed Meters/Second	Direction	Speed Meters/Second	Direction
January	5.3	WNW	5.0	NE	4.4	NW
February	5.5	W	5.2	NW	4.6	NW
March	5.6	WNW	5.4	NW	4.8	NW
April	5.5	S	5.1	WNW	4.6	S
May	4.9	S	4.5	SW	4.0	S
June	4.3	S	4.2	SW	3.8	S
July	4.1	S	3.9	SW	3.5	S
August	3.9	S	3.9	SW	3.4	S
September	4.2	ENE	4.0	SW	3.5	S
October	4.4	W	4.2	SW	3.7	N
November	5.1	W	4.6	SW	4.1	SW
December	5.1	WNW	4.8	SW	4.2	NW
AVERAGES	4.8	S	4.6	SW	4.0	S

[a] Represents 16 years of data (1955-1970)

[b] Represents 31 years of data (1940-1970)

[c] Represents 32 years of data (1939-1970)

TABLE B-4. AVERAGE WIND SPEED AND DIRECTION AT HOUSTON, TEXAS

	Houston			
	1931-1963		1969	
	Speed (m/sec)	Direction	Speed (m/sec)	Direction (degrees)
January	5.3	NNW	4.8	110
February	5.4	SSE	51.	70
March	5.7	SSE	5.4	40
April	5.8	SSE	4.5	150
May	5.2	SSE	3.7	130
June	4.6	SSE	3.0	150
July	3.9	S	2.4	180
August	3.8	SSE	2.5	130
September	4.1	SSE	2.2	80
October	4.4	ESE	3.3	90
November	5.0	SSE	2.6	10
December	5.1	SSE	3.1	90
AVERAGE	4.8	SSE	3.5	120

Wind direction for 1931-1963 is prevailing direction while that for 1969 is resultant direction.

SENSITIVITY ANALYSIS

The purpose of this sensitivity analysis is to describe the manner in which predicted ground level concentrations vary in response to changes in key input parameters. For the purpose of this analysis an emission rate of 6050 grams/hour was used.

Ground level concentration as a function of three effective stack heights is shown in Figure B-1. At an effective stack height, h, of 10.0 meters and a wind speed, u, of 0.5 meters/second, a peak concentration of 3040 $\mu g/m^3$ occurs at 0.5 km downwind. As h is doubled to 20 m, concentration is reduced to 810 $\mu g/m^3$ but now occurs further downwind at 0.9 km. Increasing the effective stack height to 30.0 m further reduces the ground level maximum concentration to 267 $\mu g/m^3$ which now occurs even further downwind at 2.0 km. An increase in the effective stack height by a factor of two causes approximately a four-fold decrease in ground level concentration and increasing the effective stack height by a factor of three causes approximately a 12-fold decrease in ground level concentration. This demonstrates the strong influence of effective stack height on ground level concentration.

The dependence of concentration on wind speed is shown in Figure B-2. Increasing wind speed by a factor of 2 reduces ground level concentration by exactly one-half. This may be inferred directly from Equation (B-1) in which concentration is inversely proportional to wind speed.

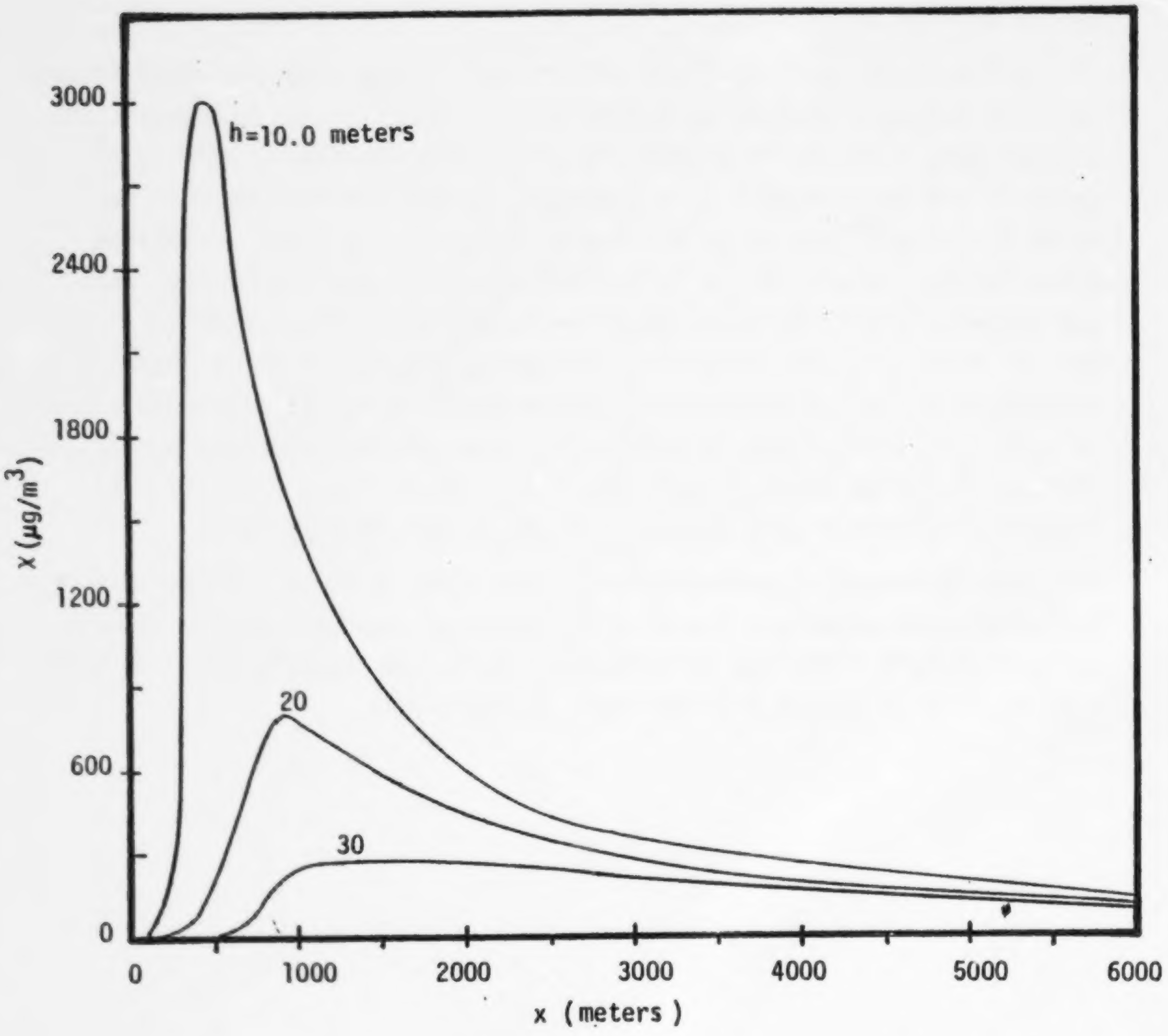

Figure B-1. Ground level concentration as a function of downwind distance at three effective stack heights, h. Emission rate is 6.05 kg/hr.

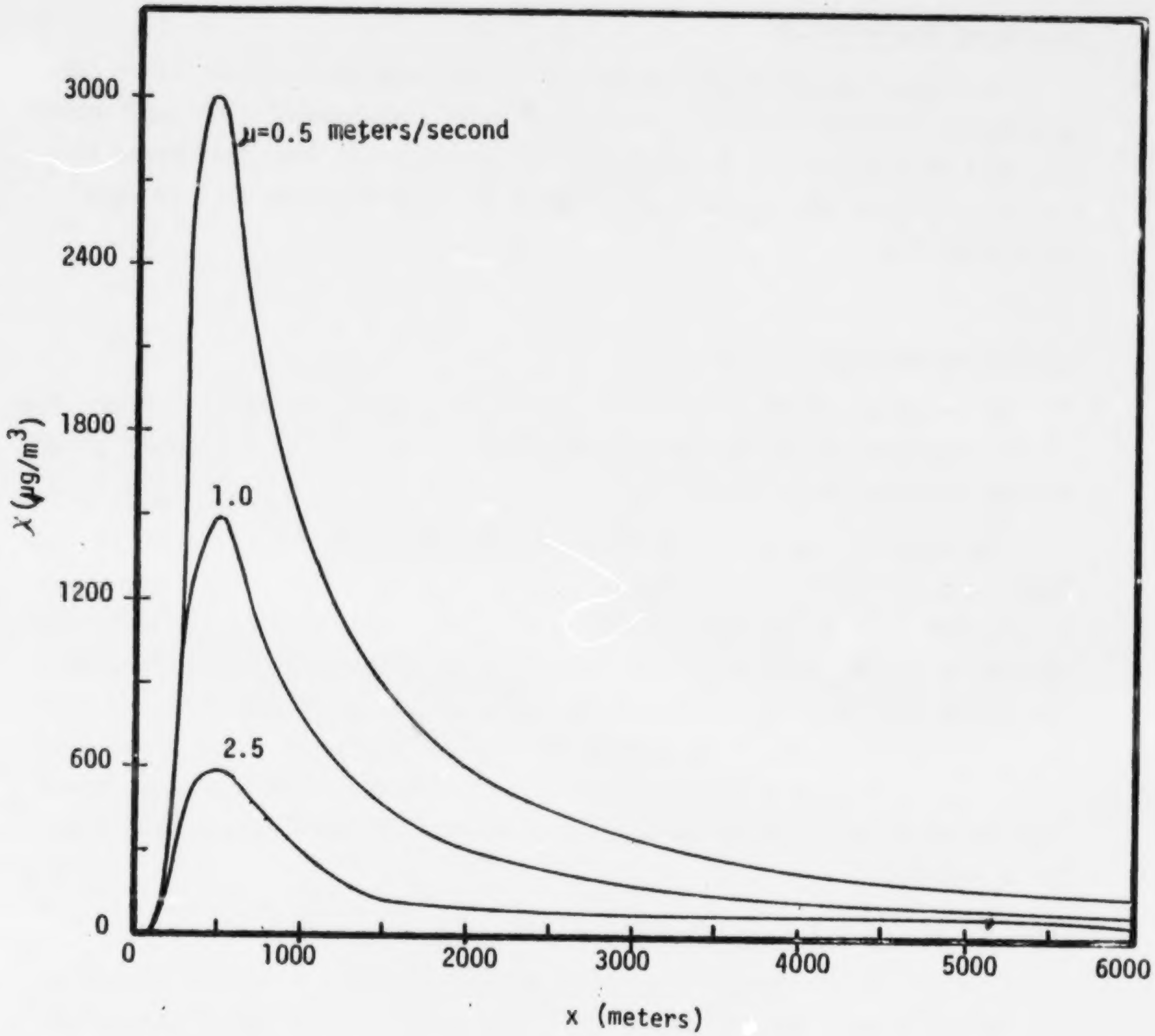

Figure B-2. Ground level concentration as a function of downwind distance at three wind speeds, u. Emission rate is 6.05 kg/hr.

SIMULATION RESULTS

Simulation of ambient air quality effects associated with at-sea incineration, land-based incineration, and the chlorolysis process was performed using the model and inputs described in previous sections and the results are shown in Tables B-5 through B-12.

Land-Based Incineration

The highest ground level concentration for land-based incineration can be expected from particulates. Table B-5 shows a maximum of 0.62 $\mu g/m^3$ occurring at 3 km downwind for D stability. Unburned wastes from land-based incineration appear small. At 3 km downwind the concentration is 0.18 $\mu g/m^3$ for D stability.

At-Sea Incineration

As shown in Tables B-6 and B-7, the highest predicted concentrations from at-sea incineration are due to HCl emissions. A maximum of 4.42 mg/m^3 occurs at 4 km downwind for D Stability.

The ambient levels for unburned wastes from at-sea incineration are much lower than for HCl. This is due to a lower emission rate for unburned waste as compared to that for HCl. In turn, the differences in emission rates are related to 1) the relatively high combustion efficiency of the incinerator, and 2) the fact that scrubbers are not used for at-sea incineration. Therefore, all HCl produced is emitted while unburned waste emissions are assumed to be, and in fact are, combustion efficiency limited. The maximum concentration for unburned waste is calculated to be 2.75 $\mu g/m^3$ at 4 km downwind for D stability.

Chlorolysis Process

The simulation results for the chlorolysis process are shown in Tables B-8 through B-12. The maximum ground level concentration for all emissions from each unit except the incineration unit occurs at the source with concentration decreasing as distance from the source increases. Because the incineration unit has a stack height of 40.0 meters, the maximum ground level concentration of emissions from the incineration unit occurs at 700 meters downwind from the source.

In Table B-13 the same emissions from each process (i.e., CCl_4 from the NaOH absorber, CCl_4 from the absorption unit, and CCl_4 from the HCl column) have been summed and the totals are shown. It is assumed that emission concentrations are additive. The maximum concentration for the summed emissions occurs at the source with concentration decreasing as distance from the source increases.

TABLE B-5. RESULTS OF AIR QUALITY SIMULATION FOR LAND-BASED INCINERATION: HCl, TRACE METALS, UNBURNED WASTE AND PARTICULATES[a]

Distance Downwind From Facility (Meters)	HCl (ng/m^3)	Trace Metals (Ti,Ni & Cr,ea) (ng/m^3)	Unburned Waste (ng/m^3)	Particulates (ng/m^3)
100	.00	.00	.00	.00
200	.00	.00	.00	.00
300	.00	.00	.00	.00
400	.00	.00	.00	.00
500	.07	.00	.02	.08
600	2.88	.00	.96	3.31
700	9.20	.01	3.09	10.59
800	31.03	.02	10.40	35.71
900	57.47	.04	19.26	66.14
1000	148.08	.11	49.63	170.41
2000	477.06	.37	159.91	549.02
3000	536.61	.41	179.87	617.55
4000	489.52	.38	164.09	563.36
5000	425.73	.33	142.70	489.95
6000	367.13	.28	123.06	422.51
7000	317.79	.25	106.52	365.72
8000	277.36	.21	92.97	319.19
9000	244.06	.19	81.81	280.87
10000	216.52	.17	72.58	249.18
20000	90.42	.07	30.31	104.05
30000	51.90	.04	17.40	59.73

[a] Simulation parameters were: Effective Stack Weight = 96.5 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-6. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: HCl, UNBURNED WASTES AND INORGANICS[a]

	GROUND LEVEL CONCENTRATION				
Distance Downwind From Ship (Meters)	HCl (ng/m^3)	Unburned Wastes ($\mu g/m^3$)		Inorganics ($\mu g/m^3$)	
		99.96% DE[b]	99.99% DE[b]	High	Low
100	.00	.00	.00	.00	.00
200	.00	.00	.00	.00	.00
300	.00	.00	.00	.00	.00
400	.00	.00	.00	.00	.00
500	.00	.00	.00	.00	.00
600	.10	.06	.00	.00	.00
700	.84	.00	.00	.00	.00
800	8.09	.01	.00	.04	.03
900	25.43	.02	.00	.13	.10
1000	144.67	.09	.02	.74	.54
2000	2082.66	1.29	.32	10.59	7.80
3000	2849.86	2.39	.60	19.58	14.41
4000	4422.80	2.75	.69	22.49	16.55
5000	4389.32	2.73	.68	22.32	16.43
6000	4116.79	2.56	.64	20.93	15.41
7000	3777.38	2.35	.59	19.21	14.14
8000	3438.65	2.14	.53	17.48	12.87
9000	3124.50	1.94	.49	15.89	11.69
10000	2843.01	1.77	.44	14.46	10.64
20000	1318.93	.82	.20	6.71	4.94
30000	781.14	.49	.12	3.97	2.92

[a] Simulation parameters were: Effective Stack Height = 125.5 meters
Wind Speed = 4.0 meters/second
D stability

[b] DE = Destruction efficiency

TABLE B-7. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: SELECTED TRACE ELEMENTS[a]

	Ground Level Concentration		
Downwind Distance From Ship (Meters)	F (ng/m^3)	Cu/Zn (ng/m^3)	Pb/Ti (ng/m^3)
100	.00	.00	.00
200	.00	.00	.00
300	.00	.00	.00
400	.00	.00	.00
500	.00	.00	.00
600	.01	.01	.00
700	.06	.04	.02
800	.57	.40	.23
900	1.80	1.26	.72
1000	10.22	7.15	4.09
2000	147.08	102.96	58.83
3000	271.08	190.32	108.75
4000	312.34	218.64	124.94
5000	309.98	216.99	123.99
6000	290.73	203.51	116.29
7000	266.76	186.73	106.71
8000	242.84	169.99	97.14
9000	220.66	154.46	88.26
10000	200.78	140.54	80.31
20000	93.14	65.20	37.26
30000	55.17	38.62	22.07

[a] Simulation parameters were: Effective Stack Height = 125.5 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-7 (Continued)

Downwind Distance From Ship (Meters)	Ground Level Concentration As/Co (ng/m^3)	Cr (ng/m^3)	Ni (ng/m^3)
100	.00	.00	.00
200	.00	.00	.00
300	.00	.00	.00
400	.00	.00	.00
500	.00	.00	.00
600	.00	.03	.01
700	.00	.24	.12
800	.06	2.28	1.14
900	.18	7.18	3.59
1000	1.02	40.87	20.43
2000	14.71	588.32	294.16
3000	27.19	1087.53	543.77
4000	31.24	1249.38	624.69
5000	31.00	1239.92	619.96
6000	29.07	1162.93	581.47
7000	26.68	1067.06	533.53
8000	24.28	971.37	485.68
9000	22.06	882.63	441.31
10000	20.08	803.11	401.56
20000	9.32	372.58	186.29
30000	5.52	220.66	110.33

TABLE B-8. RESULTS OF AIR QUALITY SIMULATION FOR CHLOROLYSIS PROCESS: EMISSIONS FROM NaOH ABSORBER[a]

Downwind Distance From Facility (meters)	Inerts ($\mu g/m^3$)	CCl_4 (ng/m^3)	$COCl_2$ (ng/m^3)	HCl (ng/m^3)
100	3351.84	167.59	3.35	10.06
200	1238.16	61.91	1.24	3.71
300	617.24	30.86	.62	1.85
400	415.08	20.75	.42	1.25
500	295.74	14.79	.30	.89
600	208.59	10.43	.21	.63
700	173.34	8.67	.17	.52
800	129.50	6.47	.13	.39
900	111.80	5.59	.11	.34
1000	91.88	4.59	.09	.28
2000	34.15	1.71	.03	.10
3000	18.76	.94	.02	.06
4000	12.27	.61	.01	.04
5000	8.82	.44	.01	.03
6000	6.74	.34	.01	.02
7000	5.36	.27	.00	.02
8000	4.41	.22	.00	.01
9000	3.70	.19	.00	.01
10000	3.17	.16	.00	.01
20000	1.14	.06	.00	.00
30000	.62	.03	.00	.00

[a] Simulation parameters were: Effective Stack Height - 5.0 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-9. RESULTS OF AIR QUALITY SIMULATION FOR CHLOROLYSIS PROCESS: EMISSIONS FROM INCINERATION UNIT[a]

Downwind Distance From Facility (meters)	Ground Level Concentration Inerts (mg/m^3)	Ground Level Concentration HCl ($\mu g/m^3$)
100	.00	.00
200	.02	.00
300	3.04	.16
400	7.45	.39
500	9.14	.48
600	12.89	.67
700	13.46	.70
800	12.98	.68
900	12.76	.66
1000	12.72	.66
2000	6.82	.36
3000	4.23	.22
4000	2.93	.15
5000	2.17	.11
6000	1.70	.09
7000	1.37	.07
8000	1.14	.06
9000	.96	.05
10000	.83	.04
20000	.30	.02
30000	.17	.01

[a] Simulation parameters were: Effective Stack Height = 40.0 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-10. RESULTS OF AIR QUALITY SIMULATION FOR CHLOROLYSIS PROCESS: EMISSIONS FROM ABSORPTION UNIT[a]

		Ground Level Concentration		
Downwind Distance From Facility (meters)	Inerts (mg/m^3)	Cl_2 (μg/m^3)	$COCl_2$ (μg/m^3)	CCl_4 (μg/m^3)
100	418.98	10.26	14.28	22.22
200	154.77	3.79	5.27	8.21
300	77.15	1.89	2.63	4.07
400	51.89	1.27	1.77	2.75
500	36.97	.90	1.26	1.96
600	26.07	.64	.89	1.38
700	21.67	.53	.74	1.15
800	16.19	.40	.55	.86
900	13.97	.34	.48	.74
1000	11.48	.28	.39	.61
2000	4.27	.10	.15	.23
3000	2.35	.06	.08	.12
4000	1.53	.04	.05	.08
5000	1.10	.03	.04	.06
6000	.84	.02	.03	.04
7000	.67	.02	.02	.04
8000	.55	.01	.02	.03
9000	.46	.01	.02	.02
10000	.40	.01	.01	.02
20000	.14	.00	.00	.01
30000	.08	.00	.00	.00

[a] Simulation parameters were: Effective Stack Height = 5.0 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-11. RESULTS OF AIR QUALITY SIMULATION FOR CHLOROLYSIS PROCESS: EMISSIONS FROM ABSORPTION TANK[a]

Downwind Distance From Facility (meters)	Ground Level Concentration SO_2 ($\mu g/m^3$)
100	1.01
200	.37
300	.19
400	.12
500	.09
600	.06
700	.05
800	.04
900	.03
1000	.03
2000	.01
3000	.01
4000	.00
5000	.00
6000	.00
7000	.00
8000	.00
9000	.00
10000	.00
20000	.00
30000	.00

[a] Simulation parameters were: Effective Stack Height = 5.0 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-12. RESULTS OF AIR QUALITY SIMULATION FOR CHLOROLYSIS PROCESS: EMISSIONS FROM HCl COLUMN[a]

	Ground Level Concentration			
Downwind Distance From Facility (meters)	HCl ($\mu g/m^3$)	Cl_2 (ng/m^3)	CCl_4 (ng/m^3)	$COCl_2$ (ng/m^3)
100	1434.59	144.13	70.39	70.39
200	529.93	53.24	26.00	26.00
300	264.18	26.54	12.96	12.96
400	177.66	17.85	8.72	8.72
500	126.58	12.72	6.21	6.21
600	89.28	8.97	4.38	4.38
700	74.19	7.45	3.64	3.64
800	55.42	5.57	2.72	2.72
900	47.85	4.81	2.35	2.35
1000	39.32	3.95	1.93	1.93
2000	14.62	1.47	.72	.72
3000	8.03	.81	.39	.39
4000	5.25	.53	.26	.26
5000	3.78	.38	.19	.19
6000	2.88	.29	.14	.14
7000	2.30	.23	.11	.11
8000	1.89	.19	.09	.09
9000	1.58	.16	.08	.08
10000	1.35	.14	.07	.07
20000	.49	.05	.02	.02
30000	.39	.03	.01	.01

[a] Simulation parameters were:
Effective Stack Height = 5.0 meters
Wind Speed = 4.0 meters/second
D stability

TABLE B-13. GROUND LEVEL CONCENTRATIONS OF EMISSIONS FROM A CHLOROLYSIS PLANT[a]

	Ground Level Concentration					
Downwind Distance From Facility (meters)	CCl_4 ($\mu g/m^3$)	HCl ($\mu g/m^3$)	Cl_2 ($\mu g/m^3$)	$COCl_2$ ($\mu g/m^3$)	SO_2 ($\mu g/m^3$)	Inerts (mg/m^3)
100	22.46	1434.60	10.40	14.35	1.01	422.33
200	8.30	529.93	3.84	5.30	.37	156.03
300	4.13	264.34	1.92	2.64	.19	80.80
400	2.78	178.05	1.29	1.78	.12	59.76
500	1.98	127.06	.91	1.27	.09	46.41
600	1.39	89.95	.65	.89	.06	39.17
700	1.16	74.89	.54	.74	.05	35.30
800	.87	56.10	.41	.55	.04	29.30
900	.75	48.51	.34	.48	.03	26.84
1000	.61	39.98	.28	.39	.03	24.29
2000	.23	14.98	.10	.15	.01	11.12
3000	.12	8.25	.06	.08	.01	6.60
4000	.08	5.40	.04	.05	.00	4.47
5000	.06	3.89	.03	.04	.00	3.28
6000	.04	2.97	.02	.03	.00	2.55
7000	.04	2.37	.02	.02	.00	2.05
8000	.03	1.95	.01	.02	.00	1.69
9000	.02	1.63	.01	.02	.00	1.42
10000	.02	1.39	.01	.01	.00	1.23
20000	.01	.51	.00	.00	.00	.44
30000	.00	.28	.00	.00	.00	.25

[a] Values obtained by adding the concentrations of the same emissions from each process.

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